SOIL WATER AND AGRONOMIC PRODUCTIVITY

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R. Lal and B. A. Stewart

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SOIL WATER AND AGRONOMIC PRODUCTIVITY

Edited by

Rattan Lal and B. A. Stewart

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Rattan Lal

Preface

Only 2.75% ($40.7 \times 10^6\,\text{km}^3$) of the world's water pools are renewable freshwater resources. Of these, polar ice caps and glaciers (melting rapidly because of climate change) constitute 2% (29.6×10^6 km^3), groundwater constitutes 0.7% ($10.36 \times 10^6\,\text{km}^3$), and all other water bodies constitute 0.05%. The latter include soil water, permafrost, and wetlands, which constitute 0.0167% ($0.25 \times 10^6\,\text{km}^3$), and freshwater lakes and rivers, which constitute about 0.033% ($0.048 \times 10^6\,\text{km}^3$). Thus, renewable freshwater supply is a scarce resource and is unequally distributed among the world regions.

More severe than the scarcity of cropland is the nonavailability of freshwater supply for the rapidly expanding world's population, with competing demands for nonagricultural uses. About 1 billion people, mostly in rural Asia and sub-Saharan Africa (SSA), do not have access to hygienically clean water. By 2050, the annual per capita available freshwater supply will be merely 503 m^3 (the minimum required is $10^3\,\text{m}^3$/year) for Egypt, 517 m^3 for Ethiopia, 543 m^3 for UAE, 690 m^3 for Iran, 791 m^3 for Burkina Faso, 803 m^3 for Zimbabwe, and 815 m^3 for Afghanistan. There will be 30 densely populated countries (e.g., Pakistan, India, and others in arid and semiarid climates) that will face severe water shortage and recurring drought stress by 2025. Water-related problems will be exacerbated by climate change and the attendant increase in the intensity and frequency of extreme events.

Hunger and related malnutrition affect 1,020 million people around the world. Of these, 230 million live in India and another 220 million in SSA. Low agronomic production is attributed to low crop yields of <1 t/ha under rainfed conditions because of recurring drought stress. Loss of grain production due to water scarcity in developing countries is estimated at 100 Mt in 1995, 300 Mt in 2025, and 425 Mt in 2050. Crop yields can be improved through soil-water conservation and increase in area under supplemental irrigation. Over a 42-year period between 1961 and 2003, cropland area under irrigation increased from 3.5 million hectares (Mha) or 8.6 million acres (Ma) to 7.0 Mha (17.3 Ma) in SSA. Only 5% of the irrigable land area is currently being irrigated in SSA. In comparison, cropland area under irrigation increased between 1961 and 2003 from 30.4 Mha (75.1 Ma) to 54.6 Mha (134.8 Ma) in China and from 24.7 Mha (61.0 Ma) to 55.8 Mha (137.8 Ma) in India.

The need for an efficient use of soil water is also enhanced by the lack of availability of freshwater supply for supplemental irrigation. Global water use for agriculture, as a percentage of the total water use, was 81.4% in 1900, 72.3% in 1950, 68.2% in 1975, and 56.7% in 2000. Global water use for urban purposes (km^3/year) was 20 in 1900, 60 in 1950, 150 in 1975, and 440 in 2000. Similarly, global water use (km^3/year) for industrial purposes was 30 in 1900, 190 in 1950, 630 in 1975, and 1900 in 2000.

Availability of water for irrigation is also constrained by the diversion to fossil fuel production and eutrophication/pollution of water resources. One liter of bioethanol production requires 3500 L of fresh water. Thus, there is a strong and prime need for conserving, recycling, and improving soil-water resources to meet the food demands of the growing world population.

The severity of drought is likely to be exacerbated by the projected climate change because of an increase in the frequency of extreme events. The abrupt climate change may increase the risks of three types of drought. These are (1) meteorological drought caused by the long-term decrease in precipitation, (2) hydrological drought by the long-term decline in surface runoff and severe fall in the groundwater levels, and (3) agronomic drought caused by the reduction in soil moisture availability because of degradation in the structural properties and retention porosity. Severe degradation, especially of soil physical and biological qualities, aggravates agronomic drought through a decrease in the effective rooting depth by accelerated erosion, a decline in the soil organic matter content by decomposition and erosion, a reduction in the magnitude and stability of aggregates, a decline in the water infiltration rate and an increase in the losses by surface runoff, and an increase in soil evaporation. Thus, agronomic yields of upland crops, especially of shallow-rooted seasonals/annuals, are adversely affected by agronomic droughts. A decline in soil fertility and an elemental imbalance, along with an increase in salinization, also impact the vulnerability of crops to drought.

Therefore, soil-water management is crucial to reducing the vulnerability to agronomic drought. Technological innovations to enhance the availability of water for agricultural crops through soil-water management depend on soil- and site-specific conditions. Crop water use can be increased by the management of surface runoff, groundwater, irrigation, and soil water. This volume is devoted to the principles and practices of enhancing water-use efficiency. This 21-chapter volume is thematically divided into seven sections: (1) Water and Agronomic Productivity (two chapters), (2) Water Resources and Agriculture (six chapters), (3) Irrigation Management (four chapters), (4) Agronomic Management of Soil and Crop (six chapters), (5) Policy (one chapter), (6) Tools of Watershed Management (one chapter), and (7) Research and Development Needs (one chapter). World-renowned scientists were invited to contribute chapters to illustrate these seven themes.

The editors thank all the authors for their outstanding contributions to this volume. Thanks are due to the staff of Taylor & Francis for their timely efforts in publishing this volume and also to the staff of the Carbon Management and Sequestration Center, who made valuable contributions. Our special thanks are due to Ms. Theresa L. Colson for her dedication and commitment in handling the editorial production of the chapters and for collaborating with the authors in the review process.

Rattan Lal
Bobby Stewart

Editors

Rattan Lal is a distinguished university professor of soil physics in the College of Food Agriculture and Environment Sciences and director of the Carbon Management and Sequestration Center, Food, Agricultural, and Environmental Sciences/Ohio Agriculture Research and Development Center, The Ohio State University. Before joining Ohio State in 1987, he was a soil physicist for 18 years at the International Institute of Tropical Agriculture, Ibadan, Nigeria. In Africa, Professor Lal conducted long-term experiments on land use; watershed management; soil erosion processes as influenced by rainfall characteristics and soil properties; methods of deforestation; soil-tillage and crop-residue management; cropping systems including cover crops and agroforestry; and mixed/relay cropping methods. He also assessed the impact of soil erosion on crop yield and related erosion-induced changes in soil properties to crop growth and yield. Since joining The Ohio State University in 1987, he has continued research on erosion-induced changes in soil quality and developed a new project on soils and climate change. He has demonstrated that accelerated soil erosion is a major factor affecting the emission of carbon from the soil to the atmosphere. Soil-erosion control and adoption of conservation-effective measures can lead to carbon sequestration and mitigation of the greenhouse effect. His other research interests include soil compaction, conservation tillage, mine soil reclamation, water table management, and sustainable use of soil and water resources of the tropics for enhancing food security. Professor Lal is a fellow of the Soil Science Society of America, American Society of Agronomy, Third World Academy of Sciences, American Association for the Advancement of Sciences, Soil and Waste Conservation Society, and Indian Academy of Agricultural Sciences. He is a recipient of the International Soil Science Award of the Soil Science Society of America, the Hugh Hammond Bennett Award of the Soil and Water Conservation Society, the 2005 Borlaug Award, and the 2009 Swaminathan Award. He also received an honorary degree of Doctor of Science from Punjab Agricultural University, India; from the Norwegian University of Life Sciences, Aas, Norway; and from the Alecu Russo Balti State University, Moldova. He is the past president of the World Association of the Soil and Water Conservation, the International Soil Tillage Research Organization, and the Soil Science Society of America. He is a member of the U.S. National Committee on Soil Science of the National Academy of Sciences (1998–2002, 2007–present). He has served on the panel on Sustainable Agriculture and the Environment in the Humid Tropics of the National Academy of Sciences. He has authored and coauthored about 1500 research papers. He has also written 15 and edited or coedited 48 books.

B.A. Stewart is a distinguished professor of soil science at West Texas A&M University, Canyon, Texas. He is also the director of the Dryland Agriculture Institute and a former director of the USDA Conservation and Production Laboratory at Bushland, Texas; past president of the Soil Science Society of America; and a member of the 1990–1993 Committee on Long-Range Soil and Water Policy, National Research Council, National Academy of Sciences. He is a fellow of the Soil Science Society of America, the American Society of Agronomy, and the Soil and Water Conservation Society; a recipient of the USDA Superior Service Award; a recipient of the Hugh Hammond Bennett Award of the Soil and Water Conservation Society; and an honorary member of the International Union of Soil Sciences in 2008. Dr. Stewart is very supportive of education and research on dryland agriculture. The B.A. and Jane Anne Stewart Dryland Agriculture Scholarship Fund was established at West Texas A&M University in 1994 to provide scholarship to undergraduate and graduate students with a demonstrated interest in dryland agriculture.

Contributors

Francisco J. Arriaga
USDA-ARS National Soil Dynamics Laboratory
Auburn, Alabama

Li Baoguo
Department of Soil and Water Sciences
China Agricultural University
Beijing, China

ElSayed Abdel Bary
Soil Science Department
Zagazig University
Sarqia, Egypt

G. Basch
Institute of Mediterranean Agricultural and Environmental Sciences
University of Evora
Evora, Portugal

R. Louis Baumhardt
USDA-ARS Conservation and Production Research Laboratory
Bushland, Texas

E. Bautista
U.S. Arid-Land Agricultural Research Center
Maricopa, Arizona

Ronald L. Bingner
USDA-ARS National Sedimentation Laboratory
Oxford, Mississippi

J. Bordovsky
Texas AgriLife Research Center
Texas A&M University System
Lubbock, Texas

K.F. Bronson
Irrigation Water Management
U.S. Arid-Land Agricultural Research Center
Maricopa, Arizona

A. Calegari
Soil Science Department
Agronomic Institute of Paraná
Londrina, Brazil

A.J. Clemmens
WEST Consultants, Inc.
Tempe, Arizona

Paul D. Colaizzi
USDA-ARS Conservation and Production Research Laboratory
Bushland, Texas

Seth M. Dabney
USDA-ARS National Sedimentation Laboratory
Oxford, Mississippi

D.R. dos Santos
Soil Science Department
Federal University of Santa Maria
Santa Maria, Brazil

Anjali Dubey
Carbon Management and Sequestration Center
The Ohio State University
Columbus, Ohio

Robert G. Evans
USDA-ARS Northern Plains Agricultural Research Laboratory
Sidney, Montana

Steve R. Evett
USDA-ARS Conservation and Production Research Laboratory
Bushland, Texas

Huang Feng
Department of Soil and Water Sciences
China Agricultural University
Beijing, China

T. Friedrich
Plant Production and Protection Division
Food and Agriculture Organization of the United Nations
Rome, Italy

Huang Gao-bao
Gansu Agricultural University
Gansu, China

Kaushal K. Garg
Resilient Dryland Systems
International Crops Research Institute for the Semi Arid Tropics
Patancheru, India

J. Gastelum
Central Arizona Project
Phoenix, Arizona

P.I. Gubiani
Soil Science Department
Federal University of Santa Maria
Santa Maria, Brazil

N.C. Hansen
Department of Soil and Crop Sciences
Fort Collins, Colorado

Terry A. Howell
USDA-ARS Conservation and Production Research Laboratory
Bushland, Texas

D.J. Hunsaker
U.S. Arid-Land Agricultural Research Center
Maricopa, Arizona

Mostafa Ibrahim
Carbon Management and Sequestration Center
The Ohio State University
Columbus, Ohio

Meharban Singh Kahlon
Department of Soil Science
Punjab Agricultural University
Ludhiana, India

A. Kassam
School of Agriculture
University of Reading
Reading, United Kingdom

Roger A. Kuhnle
USDA-ARS National Sedimentation Laboratory
Oxford, Mississippi

Rattan Lal
Carbon Management and Sequestration Center
The Ohio State University
Columbus, Ohio

Wenzhao Liu
Institute of Soil and Water Conservation
The Chinese Academy of Sciences
Yangling, China

Pritpal Singh Lubana
College of Agricultural Engineering
Punjab Agricultural University
Ludhiana, Punjab, India

P.S. Minhas
Indian Council of Agricultural Research
New Delhi, India

Ephraim Nkonya
International Food Policy Research Institute
Washington, DC

Susan A. O’Shaughnessy
USDA-ARS Conservation and Production Research Laboratory
Bushland, Texas

G.A. Peterson
Department of Soil and Crop Sciences
Fort Collins, Colorado

Xu Qiang
Ningxia University
Yinchuan, China

Raveendra Kumar Rai
Water Resources Division
DHI (India) Water & Environment Private Ltd.
New Delhi, India

J.M. Reichert
Soil Science Department
Federal University of Santa Maria
Santa Maria, Brazil

James R. Rigby
USDA-ARS National Sedimentation Laboratory
Oxford, Mississippi

Claudia Ringler
International Food Policy Research Institute
Washington, DC

Johan Rockström
Stockholm Environment Institute
Stockholm, Sweden

F.L. Santos
Institute of Mediterranean Agricultural and Environmental Sciences
University of Evora
Evora, Portugal

Z. Sheng
Texas AgriLife Research Center
Texas A&M University System
El Paso, Texas

F. Doug Shields
USDA-ARS National Sedimentation Laboratory
Oxford, Mississippi

Anil Kumar Singh
Indian Council of Agricultural Research
New Delhi, India

Vijay P. Singh
Department of Biological and Agricultural Engineering
and
Department of Civil and Environmental Engineering
Texas A&M University
College Station, Texas

B.A. Stewart
Dryland Agriculture Institute
West Texas A&M University
Canyon, Texas

Atef Swelam
Agricultural Engineering Department
Zagazig University
Zagazig, Egypt

Venkatesh Uddameri
Department of Environmental Engineering
Texas A&M University–Kingsville
Kingsville, Texas

Paul W. Unger (retired)
Formerly with: USDA-ARS Conservation and Production Research Laboratory
Bushland, Texas

C. Wang
Department of Agricultural and Applied Economics
Texas Tech University
Lubbock, Texas

Gao Wang-sheng
China Agricultural University
Beijing, China

Suhas P. Wani
Resilient Dryland Systems
International Crops Research Institute for the Semi Arid Tropics
Patancheru, India

Liang Wei-li
Agricultural University of Hebei
Baoding, China

D.G. Westfall
Department of Soil and Crop Sciences
Fort Collins, Colorado

Qingwu Xue
Texas AgriLife Research and Extension Center
Amarillo, Texas

S. Zhao
Department of Agricultural and Applied Economics
Texas Tech University
Lubbock, Texas

Section I

Water and Agronomic Productivity

1 Global Water Balance and Agronomic Production in Relation to Food Security

Raveendra Kumar Rai and Vijay P. Singh

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1.1 WATER BALANCE

The distribution of water on the earth is highly uneven; therefore, sustainable planning and management of water on the earth to ensure environmental protection, economics, and equitability and understanding of water balance are important. For a comprehensive understanding of the hydrological system and its social integration, a knowledge of the hydrologic cycle is vital. The hydrologic cycle is also fundamental to the understanding of the carbon cycle as well as the nitrogen cycle.

1.1.1 HYDROLOGIC CYCLE

The hydrologic cycle is the unending and continuous movement of water with no specific start or end point. It is characterized by its variability in space and time. Among the various reservoirs in the cycle, the oceans are the greatest reservoir of water on the earth, covering about three-fourths of the earth's surface. Water from the oceans evaporates into the atmosphere which retains it as vapor. The atmosphere then releases this vapor primarily as precipitation in the form of rain, snow, sleet, or hail. During precipitation, some of the moisture evaporates back to the atmosphere before reaching the ground, some water is intercepted by vegetation, a portion infiltrates the ground, and the remainder flows off the land into lakes, rivers, or back to the oceans. The moisture on and beneath the earth's surface is of particular importance to humans and society.

The water cycle is also intricately intertwined with many other environmental cycles, such as the transport of energy, chemicals, and sediments. About half a million cubic kilometers of water evaporates from the oceans every year, and approximately the same amount falls back as precipitation across the globe, only one-fifth of which falls on land.

Water in the hydrologic cycle can be both a benefit and a hazard, with its extreme variations being particularly dangerous. Societies can thrive in otherwise hostile climates by drawing supplemental water from the ground or diverting it from rivers, but rapid and intense precipitation or snowmelt can also cause devastating floods and contribute to soil erosion. However, more harmful are the extended periods without precipitation causing severe droughts. Such droughts cause hardships today and have contributed to the collapse of civilizations in the past.

1.1.2 GLOBAL WATER BALANCE

For global water budgeting, two conventional perspectives are generally used: (a) atmospheric perspective and (b) earth surface perspective. The global water balance from an atmospheric perspective can be expressed as follows:

$$\frac{dS_{atm}}{dt} = E - P, \tag{1.1}$$

where S_{atm} is the total amount of water stored in the entire atmosphere in the form of vapor, liquid, and solid; P and E are the corresponding global fluxes of precipitation and evapotranspiration, respectively. Equation 1.1 does not consider any loss (e.g., molecular diffusion) or gain (e.g., comet material) of water to/from outer space.

When water balance is presented from the earth surface perspective, then the water budget equation is expressed as

$$\frac{dS_{earth}}{dt} = E - P, \tag{1.2}$$

where S_{earth} is the total storage of water in the form of vapor, liquid, and solid over and within the earth's continents and oceans (surfaces and subsurfaces). To depict the processes and mechanisms of the global water cycle, more descriptive forms of Equations 1.1 and 1.2 must be used. A more descriptive form of Equation 1.2 can be expressed as

$$\frac{dS_l}{dt} + \frac{dS_o}{dt} = P_l + P_o - E_l - E_o, \tag{1.3}$$

where the subscripts l and o refer to the land and ocean components, respectively. For the water balance of the land surface, the following equation is used:

$$\frac{dS}{dt} = P - E - R. \tag{1.4}$$

For all global land surfaces, the total runoff term, R, represents the total (i.e., surface and subsurface) flow of water that reaches the oceans and is primarily the global river discharge. However, when water budgeting is considered at a smaller scale (i.e., river basins, catchments, etc.), both surface (i.e., stream/river flow and/or surface flow) and subsurface flows (i.e., groundwater and aquifer flow) would contribute more equally to the runoff terms.

On a global scale, the major reservoirs for water are the ocean, atmosphere, cryosphere (snow and ice), lithosphere (surface and groundwater), and biosphere. Table 1.1 presents the distribution of water on the earth. In the hydrologic cycle, the water is transferred between reservoirs primarily via five fluxes: precipitation, evapotranspiration, sublimation, runoff, and streamflow (Table 1.2). Additionally, there are fluxes that transfer water within a reservoir, such as advection of moisture in the air, percolation in soils, and the so-called thermohaline circulation, which conveys water to and from the ocean's surface and its depth.

1.1.3 FRESHWATER BALANCE

Relative to the salt water, the amount of useful fresh water is small. Out of the earth's total amount of water, only 2.4% of fresh water is available in glaciers, groundwater aquifer, lakes, rivers, etc. Unfortunately, these resources are not evenly distributed or easily accessible to everyone. The freshwater distribution on the earth is presented in Table 1.3.

Table 1.3 shows that most of the fresh water is available in the form of ice and permanent snow cover. However, out of 78.51% of glacial fresh water, 69% is found in Antarctic and Arctic regions. The total usable freshwater supply to the ecosystem and humans from river systems, lakes, wetlands, soil moisture, and shallow groundwater is less than 1%, which is only 0.01% of all the earth's water. However, 0.007% of all the earth's water is readily available for human consumption (WHO 1976), which indicates that fresh water on the earth is finite and unevenly distributed as well.

TABLE 1.1
Distribution of Water on Earth

Form of Water	Area Covered ('000 km^2)	Volume ('000 km^3)	Share of Water Reserves (%) Total Water Reserves	Share of Water Reserves (%) Freshwater Reserves
Oceans	361300	1338000	96.5	—
Groundwater	134800	23400[a]	1.7	—
Fresh groundwater	134800	10530	0.76	30.1
Soil moisture	82000	16.5	0.001	0.05
Glaciers and permanent snow cover	16000	24000	1.74	68.7
Antarctica	14000	22000	1.56	61.7
Greenland	1800	2300	0.17	6.68
Arctic islands	230	83.5	0.006	0.24
Mountainous areas	220	40.6	0.003	0.12
Ground ice zones of permafrost strata	21000	300	0.022	0.86
Water reserves in lakes	2000	180	0.013	—
Fresh water	1240	91	0.007	0.26
Salt water	820	85.4	0.006	—
Marsh water	2700	11.47	0.0008	0.03
Water in rivers	148800	2.12	0.0002	0.006
Biological water	510000	1.12	0.0001	0.003
Atmospheric water	510000	12.9	0.001	0.04
Total water reserves	510000	1390000	100	—
Fresh water	148800	35000	2.35	100

Source: Korzun, V.I. (ed.) *World Water Balance and Water Resources of the Earth*. No. 25 of Studies and Reports in Hydrology. UNESCO, Paris, 1978.

[a] Not including the groundwater reserves in Antarctica.

1.1.4 FRESHWATER BALANCE CONTINENTWISE

There is large spatial variability in the freshwater resource, which can be seen from the continentwise freshwater resources in the earth (Table 1.4). Based on Table 1.4, it may be stated that the glaciers and ice caps cover about 10% of the world's landmass. These are concentrated in Greenland and Antarctica and contain 70% of the world's fresh water. Unfortunately, most of these resources are located far from human habitation and are not readily accessible for human use. According to the United States Geological Survey (USGS), 96% of the world's frozen fresh water is at the South and North Poles, with the remaining 4% spread over 550,000 km^2 of glaciers and mountainous ice caps measuring about 180,000 BCM (UNEP 1992; Untersteiner 1975; WGMS 1998, 2002). Groundwater is by far the most abundant and readily available source of fresh water, followed by lakes, reservoirs, rivers, and wetlands. An analysis indicates the following: groundwater represents over 90% of the world's readily available freshwater resource (Boswinkel 2000). About 1.5 billion people depend upon groundwater for their drinking water supply (WRI, UNEP, UNDP, World Bank 1998). The amount of groundwater withdrawn annually is roughly estimated at 600–700 BCM, representing about 20% of global water withdrawals (WMO 1997). A comprehensive picture of the quantity of groundwater withdrawn and consumed annually around the world does not exist. Most freshwater lakes are located at high altitudes, with nearly 50% of the world's lakes located in Canada alone. Many lakes, especially those in arid regions, become salty through evaporation, which concentrates

TABLE 1.2
Estimates of Average Annual Precipitation (P), Evaporation (E), Runoff Rate (P − E), and Runoff Ratio ([P − E]/P)

Region	Surface Area (10^4 km^2)	P (mm/year)	E (mm/year)	P − E (mm/year)	(P − E)/P
Europe	10.0	657	375	282	0.43
Asia	44.1	696	420	276	0.40
Africa	29.8	696	582	114	0.16
Australia	8.9	803	534	269	0.33
North America	24.1	645	403	242	0.38
South America	17.9	1564	946	618	0.40
Antarctica	14.1	169	28	141	0.83
All land areas	148.9	746	480	266	0.36
Arctic Ocean	8.5	97	53	44	0.45
Atlantic Ocean	98.0	761	1133	−372	−0.49
Indian Ocean	77.7	1043	1294	−251	−0.24
Pacific Ocean	176.9	1292	1202	90	0.07
All oceans	361.1	1066	1176	−110	−0.10
Globe	510.0	973	973	0	0

Source: Pagano, T.C. and Sorooshian, S., *Encyclopedia of Hydrological Sciences*, John Wiley & Sons, New York, 2005.

TABLE 1.3
Distribution of Freshwater Resources on the Earth

S. No.	Source	Percentage Distribution
1	Glacial ice	78.51
2	Groundwater aquifer	20.64
3	Soil moisture	0.44
4	Lakes	0.38
5	Rivers	0.01
6	Atmospheric moisture	0.01

TABLE 1.4
Continentwise Freshwater Resources by Volume

Continent	Glaciers and Permanent Ice (km^3)	Wetlands, Large Lakes, Reservoirs, Rivers (km^3)	Groundwater (km^3)
Asia	60,984	30,622	7,800,000
Africa	0.2	31,776	5,500,000
Antarctica	30,109,800	—	—
Australia	180	221	1,200,000
Europe	18,216	2,529	600,000
Greenland	2,600,000	—	—
North America	90,000	27,000	4,300,000
South America	900	NA	3,000,000

Source: UNEP. *Glaciers and the Environment*. UNEP/GEMS Environment Library No. 9. p. 8. UNEP, Nairobi, Kenya, 1992.

the inflowing salts. The Caspian Sea, the Dead Sea, and the Great Salt Lake are among the world's major salt lakes. Rivers form a hydrologic mosaic, with an estimated 263 international river basins covering 45.3% (231,059,898 km^2) of the earth's land surface, excluding Antarctica (UNEP, Oregon State University et al., in preparation). The total volume of water in the world's rivers is estimated at 2,115 BCM (Groombridge and Jenkins 1998).

1.1.5 Freshwater Resources of Sample Countries

To determine the freshwater balance of a country, it is necessary to determine the renewable water resources, followed by water quality and estimation of the exploitable water resources. In computing the water resources on a countrywide basis, renewable and nonrenewable water resources need to be considered. Renewable water resources comprise the long-term mean annual flow in rivers and net groundwater availability, whereas nonrenewable water resources comprise the deep aquifer water that has a negligible rate of recharge during the human timescale.

Renewable water resources can also be categorized into natural and actual. Natural renewable water resources are the total amount of a country's water resources (internal and external resources) computed on a yearly basis, both surface water and groundwater, which is generated through the hydrological cycle. Actual renewable water resources, on the other hand, take into consideration the quantity of flow reserved to upstream and downstream countries through formal and informal agreements or treaties and possible reduction of external flow due to upstream water abstraction. Unlike the natural renewable water resources, the actual renewable water resources vary with time and consumption pattern, and therefore these resources must be associated with a specific year.

Besides this, not all natural freshwater (surface water and groundwater) resources are accessible for use. The exploitable water resources (manageable water resources or water development potential) consider such factors as the economic and environmental feasibility of storing floodwater behind dams or extracting groundwater; the physical possibility of catching water that naturally flows out to the sea; and the minimum flow requirements for navigation, environmental services, aquatic life, etc.

The total water resources of sample countries are summarized in Table 1.5, which also includes important water resource indicators, such as dependency ratio, and per capita internal and total renewable water resources of the country. The dependency ratio and per capita water resources can be defined as

$$\text{Dependency ratio} = \frac{\text{ERWR}}{\text{TRWR}} \times 100\%, \tag{1.5}$$

where ERWR and TRWR are the external and total renewable water resources of the country, respectively.

$$\text{Per capita IRWR (in m}^3\text{/year/inhab.)} = \frac{\text{IRWR}}{\text{Total population}}, \tag{1.6}$$

$$\text{Per capita TRWR (in m}^3\text{/year/inhab.)} = \frac{\text{TRWR}}{\text{Total population}}. \tag{1.7}$$

In Equations 1.6 and 1.7, units of IRWR and TRWR are in m^3/year.

Based on internal renewable water resources of sampled countries (IRWR) (Table 1.5), it may be stated that per capita water availabilities are quite less for a few countries and have large spatial variability. The per capita water availability in Pakistan is lowest among the sampled countries (i.e., 1016 lpcd), followed by South Africa (2833 lpcd) and India (3422 lpcd).

TABLE 1.5
Renewable Water Resources of Sample Countries

Parameters	Unit	Afghanistan	Australia	China	Canada	Germany
Total area	km^2	652090	7741220	9561000	9970610	357030
Total pop.	1000 inhab.	21765	19138	1252952	30757	82017
Av. ppt. (1961–1990)	km^3/year	213.4	4136.9	5994.7	5352.2	250
Internal resources: surface	km^3/year	—	440	2711.5	2840	106.3
Internal resources: groundwater	km^3/year	—	72	828.8	370	45.7
Internal resources: overlap	km^3/year	—	20	727.9	360	45
Internal resources: total	km^3/year	55	492	2812.4	2850	107
External resources: natural	km^3/year	10	0	17.2	52	47
External resources: actual	km^3/year	10	0	17.2	52	47
Total resources: natural	km^3/year	65	492	2829.6	2902	154
Total resources: actual	km^3/year	65	492	2829.6	2902	154
Dependency ratio	%	15.4	0	0.6	1.8	30.5
IRWR per capita	m^3/year/inhab.	2527	25708	2245	92662	1305
TRWR per capita	m^3/year/inhab.	2986	25708	2258	94353	1878

Parameters	Unit	India	Italy	New Zealand	Pakistan	South Africa
Total area	km^2	3287260	301340	270530	796100	1221040
Total pop.	1000 inhab.	1008937	57530	3778	141256	43309
Av. ppt. (1961–1990)	km^3/year	3558.8	250.8	468.4	393.3	603.9
Internal resources: surface	km^3/year	1222	170.5	—	47.4	43
Internal resources: groundwater	km^3/year	418.5	43	—	55	4.8
Internal resources: overlap	km^3/year	380	31	—	50	3
Internal resources: total	km^3/year	1260.5	182.5	327	52.4	44.8
External resources: natural	km^3/year	647.2	8.8	0	181.4	5.2
External resources: actual	km^3/year	636.1	8.8	0	170.3	5.2
Total resources: natural	km^3/year	1907.8	191.3	327	233.8	50
Total resources: actual	km^3/year	1896.7	191.3	327	222.7	50
Dependency ratio	%	33.9	4.6	0	76.5	10.4
IRWR per capita	m^3/year/inhab.	1249	3172	86554	371	1034
TRWR per capita	m^3/year/inhab.	1880	3325	86554	1576	1154

				United States		
Parameters	Unit	Greenland	United Kingdom	Alaska	Conterminous	Hawaii
Total area	km^2	341700	242910	—	9629090	—
Total pop.	1000 inhab.	56	59634	627	279583	1212
Av. ppt. (1961–1990)	km^3/year	759	296.3	—	5800.8	32
Internal resources: surface	km^3/year	—	144.2	—	1862	5.2
Internal resources: groundwater	km^3/year	—	9.8	—	1300	13.2
Internal resources: overlap	km^3/year	—	9	—	1162	0
Internal resources: total	km^3/year	603	145	800	2000	18.4
External resources: natural	km^3/year	0	2	180	71	0
External resources: actual	km^3/year	0	2	180	71	0
Total resources: natural	km^3/year	603	147	980	2071	18.4
Total resources: actual	km^3/year	603	147	980	2071	18.4
Dependency ratio	%	0	1.4	18.4	3.4	0
IRWR per capita	m^3/year/inhab.	10767857	2431	1276055	7153	15187
TRWR per capita	m^3/year/inhab.	10767857	2465	1563168	7407	15187

Source: FAO. Review of world water resources by country. Water Reports No. 23, Food and Agriculture Organization, Rome, 2003.

1.2 GLOBAL WARMING AND CLIMATE CHANGE

Climate is the most important driving parameter that causes year-to-year variability in socioeconomic and environmental systems including the availability of water resources. It affects the development and planning of water resources schemes, such as flood prevention and control, drought management, and food and fiber production. Further, any change in climate will increase the uncertainty in water resources planning. Apart from this, changes in the climatic pattern will have profound effects and consequences for natural and agricultural ecosystems and for society as a whole. These changes could even alter the location of the major crop production regions on the earth (Reddy and Hodges 2000). The shift in "normal weather" patterns, with their associated extreme events, will surely change the zones of crop adaptation and cultural practices required for successful crop production. Climate- and weather-induced instability in food and fiber supplies will alter social and economic stability and regional competitiveness (Reddy and Hodges 2000).

In recent years, there has been a considerable concern about global warming and climatic changes. Alteration in climate is governed by a complex system of atmospheric, land surface, and oceanic processes and their interactions. Atmospheric processes also result in an increase in surface-level ultraviolet radiation and changes in temperature and rainfall patterns. Human activities, on the other hand, are responsible for changes in ecosystems due to the increased emission rates of CO_2 and other greenhouse gases. The evidence using state-of-the-art computer models incorporating as much of the theoretical understanding of the earth's weather suggests that global warming is occurring along with shifting patterns of rainfall and incidents of extreme weather events (IPCC 2007a).

1.2.1 IMPACT ON SPACE–TIME DISTRIBUTION OF RAINFALL

Global warming will cause an increase in the atmospheric moisture content and thus an increase in the global mean precipitation. The global annual land mean precipitation had a small, but uncertain, upward trend of approximately 1.1 mm per decade (uncertainty ± 1.5 mm) over 1901–2005. During the twentieth century, precipitation generally increased from latitudes 30° to 85°N over land; but notable decreases occurred between latitudes 10°S and 30°N in the last 30–40 years. In western Africa and South Asia, a declining linear trend in rainfall was noticed during 1900–2005 with 7.5% per century (significant statistically at <1% level), whereas much of northwest India showed increased rainfall with more than 20% per century (IPCC 2007a). Figure 1.1 shows the land precipitation changes in the world. It also shows that, excluding Asian and African countries, other parts have increasing rainfall trends.

Changes in the precipitation pattern, evaporation of water from the soil, and transpiration (especially an increase in the extreme precipitation events) are expected to increase the runoff by 2060 in some parts of northern China, East Africa, and India. Runoff is important for replenishment of the water of rivers and lakes and therefore also important for irrigation and maintenance of ecosystem services. Across South Asia (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka), large populations depend on semisubsistence agriculture for their livelihoods. Rainfall in the semiarid and subhumid regions of South Asia is highly variable and unreliable, which highly influences agricultural productivity (Lal et al. 2011).

1.2.2 IMPACT ON SNOW, ICE, AND GLACIERS

The greatest asset of altitudes of more than 3500 m is the drinking water reserves that exist in the form of glaciers. These, in addition, play a buffer role in case of drought, releasing their quota of water every year to compensate for water losses in times of drought. With global

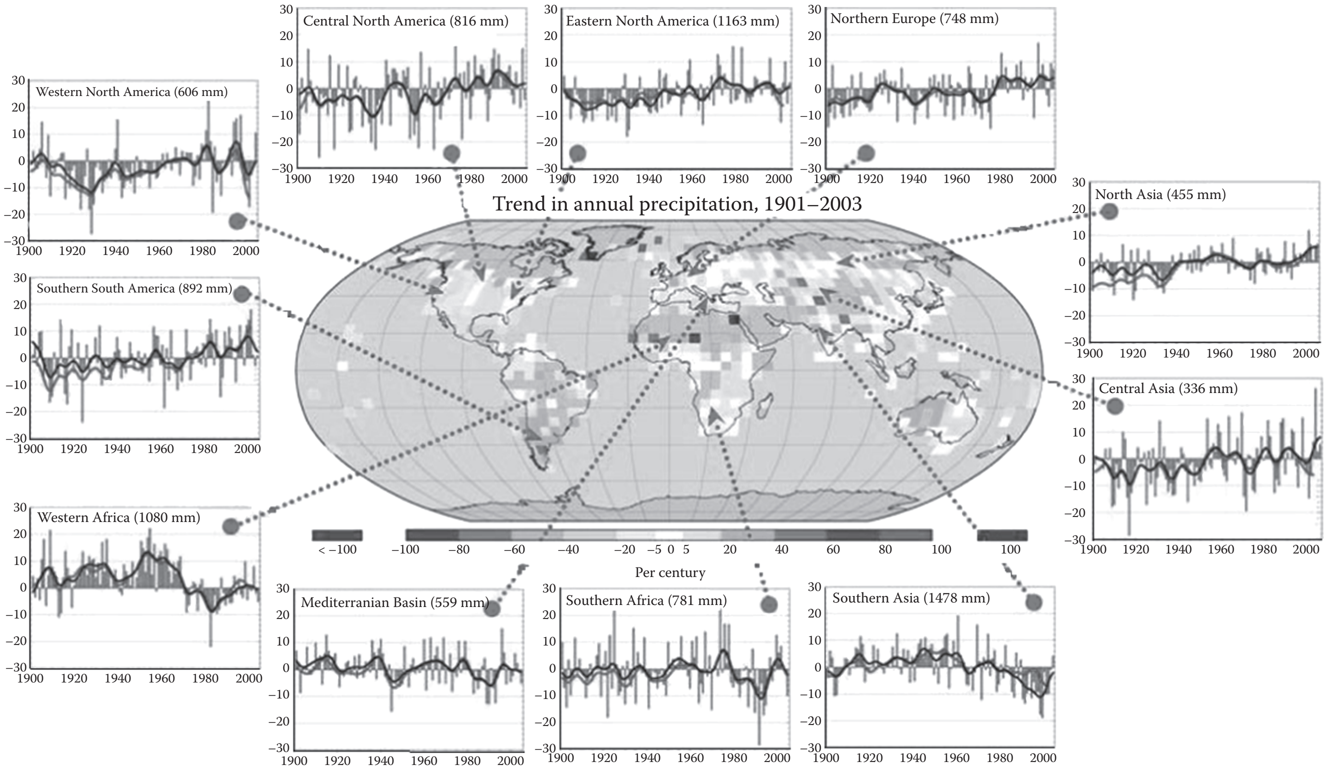

FIGURE 1.1 Global precipitation change. (From IPCC. Climate change 2007: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 2007.)

warming, however, the glaciers will be dramatically affected and consequently so will the communities located at the highest altitudes and the urban complexes located at lower altitudes. The enhanced melting as well as the increased length of the melt season of glaciers lead, at first, to increased river runoff and discharge peaks, while in a longer timeframe, the runoff is expected to decrease. The formation of lakes is occurring as glaciers retreat in several steep mountain ranges, constituting a danger for glacial lake outburst floods.

The IPCC further reported that widespread mass losses from glaciers and reductions in snow cover over recent decades are projected to accelerate throughout the twenty-first century, reducing water availability, hydropower potential, and changing the seasonality of flows in regions supplied by melt water from major mountain ranges (e.g., Hindu-Kush, Himalaya, Andes), where more than one-sixth of the world population currently lives (IPCC 2007a,b).

Central Asia, northern China, and the northern part of South Asia face immense vulnerabilities associated with the retreat of glaciers, at a rate of 10–15 m a year in the Himalayas. Seven of Asia's great river systems will experience an increase in flows over the short term, followed by a decline as glaciers melt. Climate change will be superimposed on wider pressures on water systems.

1.2.3 IMPACT ON STREAM FLOW

The current stress on water resources from population growth and economic and land-use changes, including urbanization, is expected to be exacerbated by changes in precipitation and temperature due to climate change (lead by changes in runoff and water availability). Due to climate change, the runoff is projected to increase by 10%–40% by mid-century at higher latitudes and in some wet tropical areas, including populous areas in east and southeast Asia, and decrease by 10%–30% over some dry regions at mid-latitudes and dry tropics, due to decreases in rainfall and higher rates of evapotranspiration.

The negative impacts of climate change on freshwater systems outweigh its benefits. Areas in which runoff is projected to decline face a reduction in the value of the services provided by water resources (very high confidence). The beneficial impacts of increased annual runoff in some areas are likely to be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risk (IPCC 2007a).

1.2.4 EFFECT ON FRESHWATER SUPPLIES

Water is involved in all components of the climate system (atmosphere, hydrosphere, cryosphere, land surface, and biosphere). Moreover, the hydrological cycle is intimately linked to the changes in atmospheric temperature and radiation balance, affecting it through a number of mechanisms (Bates et al. 2008).

There is a growing concern for water availability due to an increase in temperature and evaporation, a rise in sea level, and variations in rainfall patterns, thus altering the hydrological balance of many ecosystems, as well as a certainty of its negative impacts on animal and plant subsistence and of unleashing conflicts over water resources. Freshwater availability in central, south, east, and southeast Asia, particularly in large river basins, will affect more than a billion people by the 2050s (Parry et al. 2007).

Further, prolonged and repeated droughts can cause loss of crop/animal production, undermining the sustainability of livelihood systems, especially of those based on rainfed agriculture. Figure 1.2 provides a landscape of the vulnerability of freshwater resources around the world. The land precipitation trend showed an increase over the twentieth century between 30°N and 85°N; however, prominent decreases have occurred in the past 40 years (Bates et al. 2008).

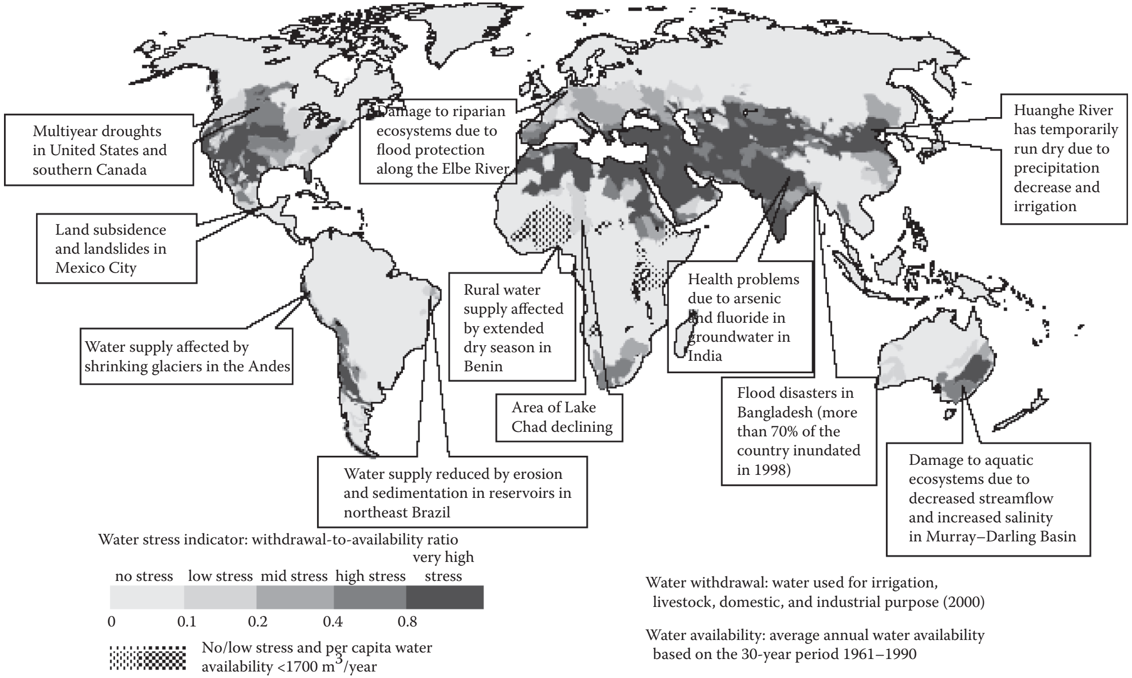
Multiyear droughts in United States and southern Canada
Land subsidence and landslides in Mexico City
Water supply affected by shrinking glaciers in the Andes
Damage to riparian ecosystems due to flood protection along the Elbe River
Rural water supply affected by extended dry season in Benin
Area of Lake Chad declining
Water supply reduced by erosion and sedimentation in reservoirs in northeast Brazil
Health problems due to arsenic and fluoride in groundwater in India
Flood disasters in Bangladesh (more than 70% of the country inundated in 1998)
Huanghe River has temporarily run dry due to precipitation decrease and irrigation
Damage to aquatic ecosystems due to decreased streamflow and increased salinity in Murray–Darling Basin
Water stress indicator: withdrawal-to-availability ratio
no stress
low stress
mid stress
high stress
very high stress
0
0.1
0.2
0.4
0.8
No/low stress and per capita water availability <1700 m³/year
Water withdrawal: water used for irrigation, livestock, domestic, and industrial purpose (2000)
Water availability: average annual water availability based on the 30-year period 1961–1990

FIGURE 1.2 Example of current vulnerabilities of freshwater resources. (From Bates, B.C., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P. (eds). Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, Secretariat IPCC, Geneva, 2008.)

1.2.5 IMPACT ON HYDROLOGICAL EXTREMES

Increased temperature and heavy rainfall events due to climate change will result in increased flood frequency and severity. Based on the available evidence, it may be stated that a significant future increase in heavy rainfall events in many regions will take place including some in which the mean rainfall is projected to decrease. The resulting increased flood risk poses challenges to society, physical infrastructure, and water quality. On the other hand, a decrease in the number of rainy days in a hydrologic year will increase the frequency and severity of the drought.

It is likely that up to 20% of the world population will live in areas where river flood potential could increase. Increases in the frequency and severity of floods and droughts are projected to adversely affect sustainable development. Increased temperatures will further affect the physical, chemical, and biological properties of freshwater lakes and rivers, with predominantly adverse impacts on many individual freshwater species, community composition, and water quality. In coastal areas, rising sea levels will exacerbate water resource constraints due to increased salinization of groundwater supplies (IPCC 2007a,b). Effects will be largest in the densely populated and low-lying mega deltas of Asia and Africa, while small islands are especially vulnerable (IPCC 2007a).

Due to climate change and reduced extent of rainfall periods, many semiarid areas (e.g., the Mediterranean Basin, western United States, southern Africa, and northeastern Brazil) will suffer with decreases in water resources. Drought-affected areas are projected to increase in extent, with the potential for adverse impacts on multiple sectors such as agriculture, water supply, energy production, and health. Regionally, large increases in irrigation water demand as a result of climate changes are projected (IPCC 2007a,b).

1.2.6 IMPACT ON TEMPERATURE

It has been established that global surface warming took place at a rate of 0.74 ± 0.18°C over the period of 1906–2005 (IPCC 2007a), and it is expected to be more in the next century than what has occurred during the past 10,000 years (IPCC 2007a). Figure 1.3 illustrates the range of historical temperature increases since the 1850s.

Particularly in India, based on the data for the period 1901–2005, it can be shown that the all-India mean annual temperature has been rising at 0.05°C/decade, with the maximum temperature at +0.07°C/decade and the minimum temperature at +0.02°C/decade (Kothawale and Kumar 2005). As a result, the diurnal temperature range shows an increase of 0.05°C/decade. However, in northern India, the average temperature is falling at a rate of −0.38°C and is unlikely to rise in all-India average temperature (i.e., at +0.42°C/century) (Arora et al. 2005).

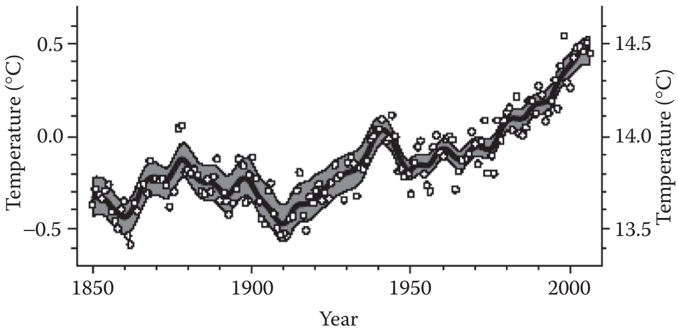

FIGURE 1.3 Global average surface temperature. (From IPCC. Climate change 2007: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 2007.)

1.2.7 IMPACT ON EVAPOTRANSPIRATION

Evapotranspiration is directly related to temperature changes. However, the extent of impact will be spatial. The rate of evapotranspiration affects the crop water requirement and thus freshwater demands for irrigation. In recent years, the demand for irrigation on account of climate changes and drastic land-use pattern changes has exacerbated so much that the dependability on groundwater has increased. As a result, in the Indian subcontinent, nearly 50% of administrative blocks have been declared “dark zones.”

1.2.8 IMPACT ON ECOSYSTEMS

Based on the IPCC (2007a), it has been stated that the resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other global change drivers, namely, land-use change, pollution, fragmentation of natural systems, and overexploitation of resources.

Over the course of this century, the net carbon uptake by terrestrial ecosystems is *likely* to peak before mid-century and then weaken or even reverse, thus amplifying climate change (IPCC 2007a).

For increases in the global average temperature exceeding 1.5°C–2.5°C and in the associated atmospheric CO_2 concentrations, major changes have been projected in ecosystem structure and function, species’ ecological interactions, and shifts in species’ geographical ranges, with largely negative consequences for biodiversity and ecosystem goods and services such as water and food supply (IPCC 2007a).

More specifically, the timing of phenological events such as flowering is often related to environmental variables, such as temperature. Changing environments are, therefore, expected to lead to changes in the life cycle, and these have been recorded for many species of plants (Parmesan and Yohe 2003). These changes have the potential to lead to asynchrony between species, or to change competition between plants. Flowering times in British plants, for example, have changed, leading to annual plants flowering earlier than perennials and insect-pollinated plants flowering earlier than wind-pollinated plants, with potential ecological consequences (Fitter and Fitter 2002). A recently published study has used data recorded by the writer and naturalist Henry David Thoreau to confirm the effects of climate change on the phenology of some species in the area of Concord, Massachusetts (Willis et al. 2008).

An overwhelming majority of studies of regional climate effects on terrestrial species reveal consistent responses to warming trends, including pole-ward and elevation range shifts of flora and fauna. Responses of terrestrial species to warming across the Northern Hemisphere are well documented by changes in the timing of growth stages (i.e., phenological changes), especially the earlier onset of spring events, migration, and lengthening of the growing season (IPCC 2007a). In various regions across the world, some high-altitude and high-latitude ecosystems have already been affected by changes in climate. The IPCC (2007a) report reviewed relevant published studies of biological systems and concluded that 20%–30% of the species assessed may be at risk of extinction from climate change impacts within this century if global mean temperatures exceed 2°C–3°C (3.6°F–5.4°F) relative to preindustrial levels.

These changes can cause adverse or beneficial effects on species. For example, climate change may benefit certain plant or insect species by increasing their ranges. The resulting impacts on ecosystems and humans, however, may be positive or negative, depending on whether these species are invasive (e.g., weeds or mosquitoes) or if they are valuable to humans (e.g., food crops or pollinating insects). The risk of extinction may increase for many species, especially those that are already endangered or at risk due to isolation by geography or human development, low population numbers, or a narrow temperature tolerance range.

Observations of ecosystem impacts are difficult to use in future projections because of the complexities involved in human–nature interactions (e.g., land-use change). Nevertheless, the observed changes are compelling examples of how rising temperatures can affect the natural world and raise questions of how vulnerable populations will adapt to the direct and indirect effects of climate change.

1.2.9 IMPACT ON AGRICULTURE

Climate change will affect rainfall, temperature, and water availability for agriculture in vulnerable areas (IPCC 2007c). For example, drought-affected areas in South Asia will experience losses in agricultural production, undermining efforts to cut rural poverty. According to the Fourth Assessment Report of the IPCC, South Asia is very likely to get warm during this century, putting pressure on some of the prime productive land and reducing agricultural output, biodiversity, and the natural ability of ecosystems to recover. It is expected that climate change impacts will be uneven between countries and regions within Asia: China with 140 million undernourished people should gain 100 million tons in cereal production; India, in turn, with 200 million undernourished people is expected to lose 30 million tons (Bates et al. 2008).

Assuming a 4.4°C increase in temperature and a 2.9% increase in precipitation, the global agricultural output potential is likely to decrease by about 6% or 16% without carbon fertilization (GRID-Arendal and Ahlenius 2007). Climate change has led to projections that by the year 2080, agricultural output potential may be reduced by up to 60% for several African countries, with an average of 16%–27% (Figure 1.4).

At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1°C–2°C), which would increase food risk (IPCC 2007a).

This climate–food interaction will affect the poor. In some industrial and industrializing nations, climate change creates new patterns of food production, causing the development of new exporting and importing zones. The access to supplies and the energy to import may become strategic concerns and lead to international conflicts. Besides, popular discontent over livelihood security was

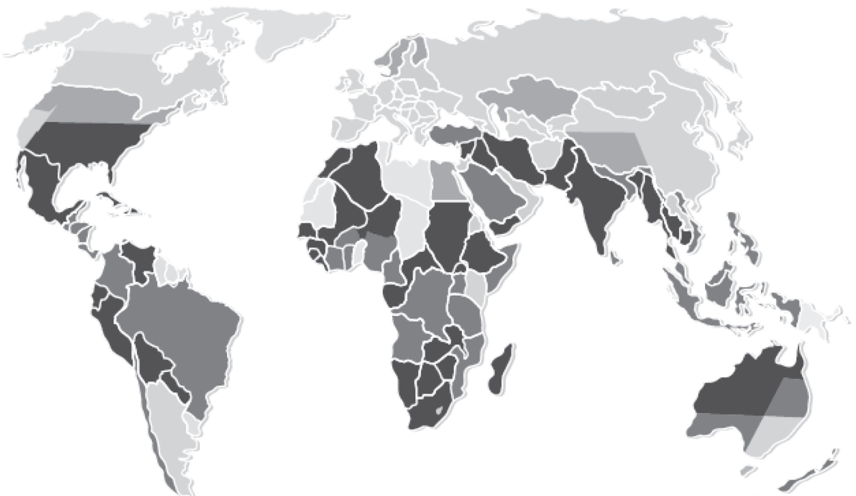

FIGURE 1.4 Projected losses in food grain due to climate change by 2080. (From UNEP. The environmental food crisis: The environment's role in averting future food crises. A UNEP rapid response assessment, United Nations Environment Programmes, Norway, 2009.)

a contributing cause for instability in Africa during the 1980s and 1990s. The same pressures will cause considerable population movements and displacement both within countries and internationally, which, in turn, will increase insecurity in its hard meaning.

1.2.10 IMPACT ON HUMAN HEALTH

Climate change indirectly influences human health on a large scale. According to IPCC (2007a,b) reports, the health status of millions of people is projected to be affected through, for example, increases in malnutrition; increased deaths, diseases, and injuries due to extreme weather events; increased burden of diarrhea diseases; increased frequency of cardiorespiratory diseases due to higher concentration of ground-level ozone in urban areas related to climate change; and the altered spatial distribution of some infectious diseases.

Climate change is projected to bring some benefits in temperate areas, such as fewer deaths from cold exposure, and some mixed effects, such as changes in the range and transmission potential of malaria in Africa (WHO 2008). Overall, it is expected that benefits will be outweighed by negative health effects of rising temperature, especially in developing countries. Critically important will be the factors that directly shape the health of populations, such as education, health care, public health initiatives, and infrastructure and economic development.

1.2.11 IMPACT ON ENERGY

Energy production and use are sensitive to changes in climate. For example, increasing temperatures will reduce the consumption of energy for heating but increase the energy used for cooling buildings (IPCC 2007b). The implications of climate change for energy supply are less clear than those for energy demand. The net effects of these changes on energy production, energy use, and utility bills will vary by region and by season.

The effects of climate change on energy supply and demand will depend not only on climatic factors but also on patterns of economic growth, land use, population growth and distribution, technological change, and social and cultural trends that shape individual and institutional actions.

There may also be changes in energy consumed for other climate-sensitive processes, such as pumping water for agricultural irrigation. Rising temperatures and associated increases in evaporation may increase the energy needs for irrigation, particularly in dry regions, such as the western United States.

On the other hand, less research has been undertaken on the impact of climate change on energy production. Some of the possible effects may be as follows:

- Hydropower generation is the energy source that is likely to be most directly affected by climate change because it is sensitive to the amount, timing, and geographical pattern of precipitation and temperature. Furthermore, hydropower needs may increasingly conflict with other priorities, such as salmon restoration goals in the Pacific Northwest (IPCC 2007c). However, changes in precipitation are difficult to project at the regional scale, which means that climate change will affect hydropower either positively or negatively, depending on the region.
- Infrastructure for energy production, transmission, and distribution may be affected by climate change. For example, if a warmer climate is characterized by more extreme weather events such as windstorms, ice storms, floods, tornadoes, and hail, the transmission systems of electric utilities may experience a higher rate of failure, with attendant costs (IPCC 2007a).
- Power plant operations can be affected by extreme heat waves. For example, the intake water that is normally used to cool the power plants becomes warm enough during extreme heat events that it compromises power plant operations.

- Some renewable sources of energy can be affected by climate change, although these changes are very difficult to predict. If climate change leads to increased cloudiness, solar energy production can be reduced. Wind energy production would be reduced if wind speeds increase above or fall below the acceptable operating range of the technology. Changes in growing conditions can affect biomass production, transportation, and power plant fuel sources, which are starting to receive more attention (IPCC 2007a).

1.3 GLOBAL POPULATION

The global population is the total population of humans on the planet Earth, which is currently estimated to be 6.92 billion by the U.S. Census Bureau (http://www.census.gov/ipc/www/popclock-world.html). The world population has experienced continuous growth since the end of the Bubonic Plague, the Great Famine, and the Hundred Years War in 1350, with a population of 300 million (IDB 2010). The highest rates of growth—increases above 1.8% per year—were seen briefly during the 1950s and for a longer period during the 1960s and 1970s; the growth rate peaked at 2.2% in 1963 and declined to 1.1% by 2009. Annual births have reduced to 140 million since their peak at 173 million in the late 1990s and are expected to remain constant, while deaths number 57 million per year and are expected to increase to 80 million per year by 2040. Current projections show a continued increase of population (but a steady decline in the population growth rate), with the population expected to reach between 7.5 and 10.5 billion in the year 2050. Based on the projection (UN 2009), the world population growth is shown in Figure 1.5.

In the earth's total population, Asia accounts for over 60% with more than 4 billion people. China and India together have about 37% of the earth's population. Africa follows with 1 billion people, 15% of the world's population. Europe's 733 million people make up 11% of the world's

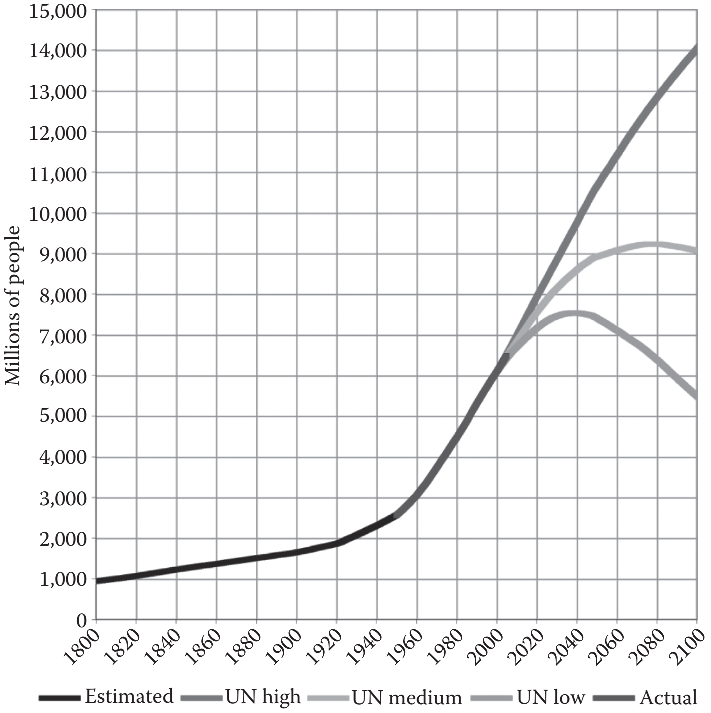

FIGURE 1.5 World population from 1800 to 2100, based on UN (2009) projections and U.S. Census Bureau historical estimates.

population. Latin America and the Caribbean region have a population of 589 million (9%), North America is home to 352 million (5%), and Oceania is home to 35 million (less than 1%) (UN 2009). Based on the latest UN projection, the world's population will be about 9.1 billion by 2050, which is 30% more than the current population of 6.9 billion.

1.3.1 DEMOGRAPHICS

The increment in the world's population based on the UN projection (UN 2009) is shown in Figure 1.5, which reveals that the population has increased at a faster rate during 1940–2000 and will be expected to increase up to the years 2040 or 2070. The regional population increase at a temporal scale is shown in Figure 1.6, which shows that Asia and Africa have the largest shares in the population. Figure 1.7 shows the population distribution pattern of the world, whereas the spatial

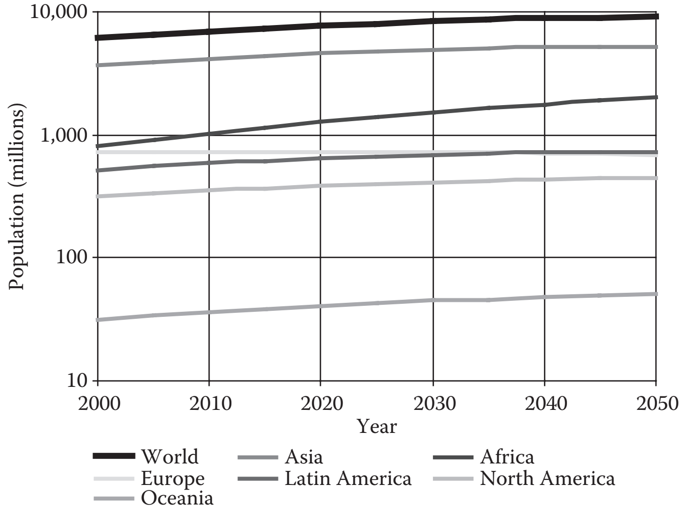

FIGURE 1.6 Population at temporal scale.

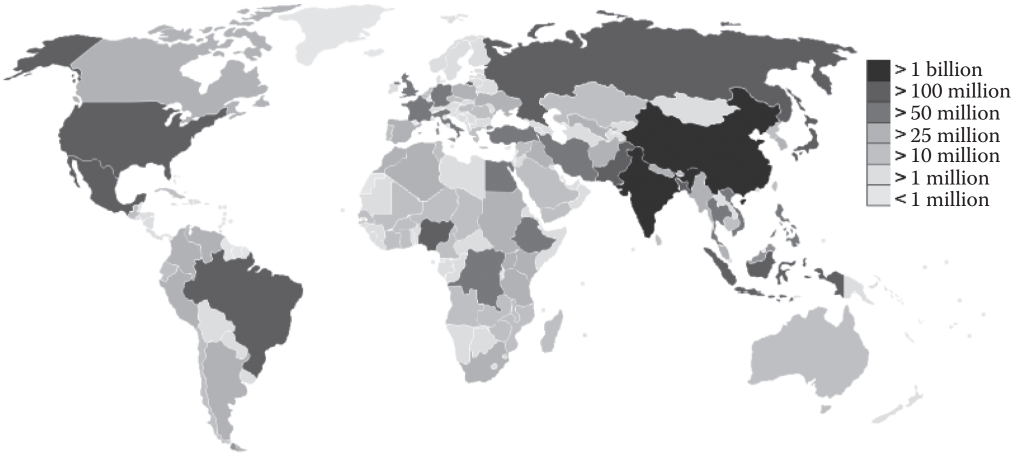

FIGURE 1.7 Spatial distribution of global population. (From UN. World urbanization prospects: The 1994 Revision. United Nations Population Division, Department for Economic and Social Information and Policy Analysis, New York, 1994.)

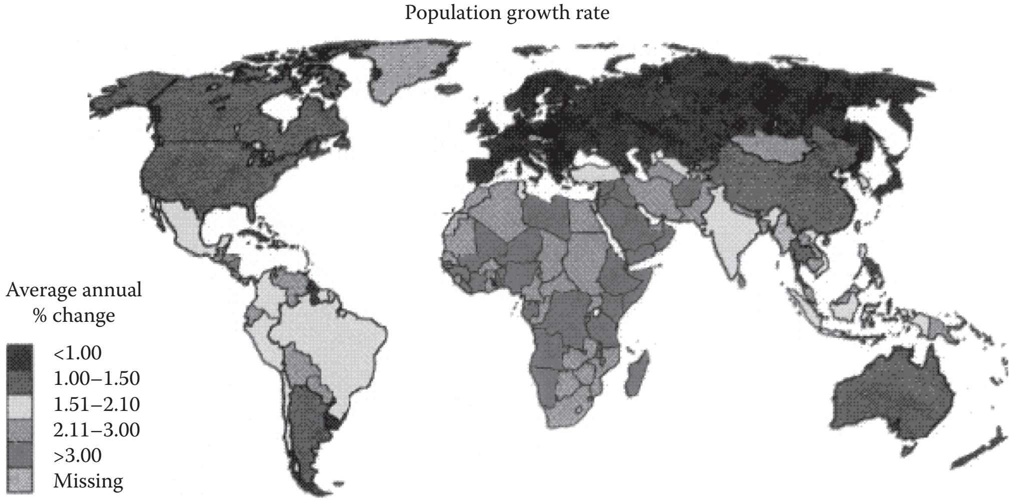

FIGURE 1.8 Spatial variation of population growth rate. (From UN. World urbanization prospects: The 1994 Revision. United Nations Population Division, Department for Economic and Social Information and Policy Analysis, New York, 1994.)

variation in population growth is depicted in Figure 1.8 (UN 1994). The countrywise population and population density are presented in Table 1.6.

1.4 DEMANDS FOR FRESH WATER

Reflecting on the water resources that will be available for future use, Hossain et al. (2011) have separated societally and environmentally important water resources into five major categories: water, food, energy, human health, and ecosystem function. These categories are interrelated, and water is required for each of the remaining four categories. The water that would be available will depend on the demands or stressors placed on the water resources and the uses thereof. This will apply to both the quantity and quality of water resources. Some of the stressors may entail local human population requirements; irrigation, floods, and droughts; biofuel production; weather variability and long-term change; land management practices; waste generation and treatment; animal and insect dynamics; vehicular and industrial emissions; natural landscape change; natural events, such as earthquakes; and others.

Uses of fresh water can be categorized as consumptive and nonconsumptive (sometimes called "renewable"). The use of water is referred to as consumptive when water is not immediately available for another use, although the final product can be directly consumed. For example, irrigation water is consumptive, because the final product is the farm produce associated with losses due to subsurface seepage and evaporation. Water that can be treated and returned as surface water, such as sewage, is generally considered nonconsumptive if that water can be put to additional use. Water use in power generation and industry is generally described using an alternate terminology, focusing on separate measurements of withdrawal and consumption. Withdrawal describes the removal of water from the environment, while consumption describes the conversion of fresh water into some other form, such as atmospheric water vapor or contaminated waste water.

In general, water used by farmers is 75% of the total water used, whereas industrial water use is only of the order of 22%. The water use for domestic and municipal demands is much less and is of the order of 0.10%.

TABLE 1.6
Countrywise Global Population and Domestic Wastewater Generation

S. No.	Country/Regions	Population	Area (km²)	Density (per km²)	Domestic Demand (MCM per Year)	Wastewater Generation (MCM per Year)
	World (land only, excl. Antarctica)	**6,919,484,600**	134,940,000	51	126280.59	101024.48
	World (land only)	**6,919,484,600**	148,940,000	46	126280.59	101024.48
	World (with water)	**6,919,484,600**	510,072,000	14	126280.59	101024.48
1	Macau (China)	541,200	29.2	18,534	9.88	7.90
2	Monaco	33,000	1.95	16,923	0.60	0.48
3	Singapore	5,076,700	710.2	7,148	92.65	74.12
4	Hong Kong (China)	7,003,700	1,104	6,349	127.82	102.25
5	Gibraltar (United Kingdom)	31,000	6.8	4,559	0.57	0.45
6	Vatican City	826	0.44	1,877	0.02	0.01
7	Malta	416,333	316	1,318	7.60	6.08
8	Bermuda (United Kingdom)	65,000	53	1,226	1.19	0.95
9	Bangladesh	162,221,000	143,998	1,127	2960.53	2368.43
10	Saint Maarten (Netherlands)	37,429	34	1,101	0.68	0.55
11	Bahrain	791,000	720	1,099	14.44	11.55
12	Maldives	309,000	298	1,037	5.64	4.51
13	Guernsey	65,726	78	843	1.20	0.96
14	Jersey	92,500	116	797	1.69	1.35
15	Saint-Martin (France)	35,263	53.2	663	0.64	0.51
16	Taiwan	23,069,345	35,980	639	421.02	336.81
17	Mauritius	1,288,000	2,040	631	23.51	18.80
18	Barbados	256,000	430	595	4.67	3.74
19	Aruba (Netherlands)	107,000	193	554	1.95	1.56
20	Palestinian territories (status disputed)	3,050,000	6,020	507	55.66	44.53
21	San Marino	30,800	61	505	0.56	0.45
22	Mayotte (France)	186,452	374	499	3.40	2.72
23	South Korea	48,456,369	99,538	487	884.33	707.46
24	Nauru	10,000	21	476	0.18	0.15
25	Puerto Rico (United States)	3,982,000	8,875	449	72.67	58.14
26	Curaçao (Netherlands)	142,180	444	446	2.59	2.08
27	Lebanon	4,224,000	10,452	404	77.09	61.67
28	Saint-Barthélemy (France)	8,450	21	402	0.15	0.12
29	Tuvalu	10,441	26	402	0.19	0.15
30	Netherlands	16,670,000	41,526	401	304.23	243.38
31	Rwanda	9,998,000	26,338	380	182.46	145.97
32	Israel	7,697,600	20,770	371	140.48	112.38
33	India	1,210,193,422	3,287,240	368	22086.03	17668.82
34	Haiti	10,033,000	27,750	362	183.10	146.48
35	Martinique (France)	402,000	1,128	356	7.34	5.87
36	Belgium	10,827,519	30,528	355	197.60	158.08
37	Marshall Islands	62,000	181	343	1.13	0.91

(*continued*)

TABLE 1.6 (Continued)
Countrywise Global Population and Domestic Wastewater Generation

S. No.	Country/Regions	Population	Area (km^2)	Density (per km^2)	Domestic Demand (MCM per Year)	Wastewater Generation (MCM per Year)
38	Japan	127,387,000	377,873	337	2324.81	1859.85
39	American Samoa (United States)	67,000	199	337	1.22	0.98
40	Guam (United States)	178,000	549	324	3.25	2.60
41	Saint Lucia	172,000	539	319	3.14	2.51
42	Virgin Islands (United States)	110,000	347	317	2.01	1.61
43	Réunion (France)	785,139	2,510	313	14.33	11.46
44	Sri Lanka	20,238,000	65,610	308	369.34	295.47
45	Philippines	92,226,600	300,076	307	1683.14	1346.51
46	Comoros	676,000	2,235	302	12.34	9.87
47	Grenada	104,000	344	302	1.90	1.52
48	Burundi	8,303,000	27,834	298	151.53	121.22
49	El Salvador	6,163,000	21,041	293	112.47	89.98
50	Saint Vincent and the Grenadines	109,000	388	281	1.99	1.59
51	Trinidad and Tobago	1,339,000	5,130	261	24.44	19.55
52	Vietnam	85,789,573	331,689	259	1565.66	1252.53
53	United Kingdom	62,041,708	243,610	255	1132.26	905.81
54	Guadeloupe (France)	405,000	1,628	249	7.39	5.91
55	Jamaica	2,719,000	10,991	247	49.62	39.70
56	Germany	81,757,600	357,022	229	1492.08	1193.66
57	Liechtenstein	35,981	160	225	0.66	0.53
58	Cayman Islands (United Kingdom)	56,000	264	212	1.02	0.82
59	Pakistan	176,090,000	803,940	219	3213.64	2570.91
60	Dominican Republic	10,090,000	48,671	207	184.14	147.31
61	Italy	60,200,060	301,318	200	1098.65	878.92
62	North Korea	24,051,706	120,538	200	438.94	351.15
63	Nepal	29,331,000	147,181	199	535.29	428.23
64	Saint Kitts and Nevis	52,000	261	199	0.95	0.76
65	Antigua and Barbuda	88,000	442	199	1.61	1.28
66	Luxembourg	502,207	2,586	194	9.17	7.33
67	Switzerland	7,761,800	41,284	188	141.65	113.32
68	Northern Mariana Islands (United States)	87,000	464	188	1.59	1.27
69	Seychelles	84,000	455	185	1.53	1.23
70	Andorra	86,000	468	184	1.57	1.26
71	Sao Tome and Principe	163,000	964	169	2.97	2.38
72	Kuwait	2,985,000	17,818	168	54.48	43.58
73	Nigeria	154,729,000	923,768	167	2823.80	2259.04
74	Anguilla (United Kingdom)	15,000	91	165	0.27	0.22
75	Federated States of Micronesia	111,000	702	158	2.03	1.62
76	British Virgin Islands (United Kingdom)	23,000	151	152	0.42	0.34
77	Gambia	1,705,000	11,295	151	31.12	24.89

TABLE 1.6 (Continued)
Countrywise Global Population and Domestic Wastewater Generation

S. No.	Country/Regions	Population	Area (km²)	Density (per km²)	Domestic Demand (MCM per Year)	Wastewater Generation (MCM per Year)
78	Isle of Man	80,000	572	140	1.46	1.17
79	Tonga	104,000	747	139	1.90	1.52
80	China	1,344,100,000	9,640,821	139	24529.83	19623.86
81	Kiribati	99,350	726	137	1.81	1.45
82	Uganda	32,710,000	241,038	136	596.96	477.57
83	Transnistria (Moldova)	555,347	4,163	133	10.14	8.11
84	Czech Republic	10,532,770	78,866	134	192.22	153.78
85	Guatemala	14,027,000	108,889	129	255.99	204.79
86	Malawi	15,263,000	118,484	129	278.55	222.84
87	Qatar	1,409,000	11,000	128	25.71	20.57
88	Denmark	5,532,531	43,094	128	100.97	80.77
89	Cape Verde	506,807	4,033	126	9.25	7.40
90	Thailand	64,232,760	513,115	125	1172.25	937.80
91	Poland	38,163,895	312,685	122	696.49	557.19
92	Indonesia	237,556,363	1,904,569	121	4335.40	3468.32
93	Moldova	3,567,500	33,844	105	65.11	52.09
94	Syria	21,906,000	185,180	118	399.78	319.83
95	Togo	6,619,000	56,785	117	120.80	96.64
96	Portugal	10,636,888	92,391	115	194.12	155.30
97	Tokelau (New Zealand)	1,378	12	115	0.03	0.02
98	France (Metropolitan)	62,793,432	551,500	114	1145.98	916.78
99	Slovakia	5,424,057	49,033	111	98.99	79.19
100	Albania	3,195,000	28,748	111	58.31	46.65
101	Armenia	3,230,100	29,800	108	58.95	47.16
102	Hungary	10,013,628	93,032	108	182.75	146.20
103	Dominica	78,940	751	105	1.44	1.15
104	Azerbaijan	8,896,900	86,600	103	162.37	129.89
105	Cuba		109,886	102		
106	Slovenia	2,075,456	20,256	102	37.88	30.30
107	Serbia (excluding Kosovo)	7,800,000	77,474	101	142.35	113.88
108	Ghana	23,837,000	238,533	100	435.03	348.02
109	Austria	8,372,930	83,858	100	152.81	122.24
110	Turkey	77,804,122	783,562	93	1419.93	1135.94
111	Spain	46,087,170	506,030	91	841.09	672.87
112	Romania	21,466,174	238,391	90	391.76	313.41
113	Costa Rica	4,579,000	51,100	90	83.57	66.85
114	Cyprus	801,851	9,251	87	14.63	11.71
115	Malaysia	28,306,700	329,847	86	516.60	413.28
116	Greece	11,306,183	131,957	86	206.34	165.07
117	Cook Islands (New Zealand)	20,000	236	85	0.37	0.29
118	Republic of Macedonia	2,114,550	25,713	82	38.59	30.87
119	Cambodia	14,805,000	181,035	82	270.19	216.15
120	Sierra Leone	5,696,000	71,740	79	103.95	83.16
121	Benin	8,935,000	112,622	79	163.06	130.45

(*continued*)

TABLE 1.6 (Continued)
Countrywise Global Population and Domestic Wastewater Generation

S. No.	Country/Regions	Population	Area (km²)	Density (per km²)	Domestic Demand (MCM per Year)	Wastewater Generation (MCM per Year)
122	Turks and Caicos Islands (United Kingdom)	33,000	417	79	0.60	0.48
123	Northern Cyprus (status disputed)	264,172	3,355	79	4.82	3.86
124	Croatia	4,443,000	56,538	79	81.08	64.87
125	Ukraine	46,936,000	603,700	78	856.58	685.27
126	Egypt	79,799,922	1,001,449	80	1456.35	1165.08
127	Wallis and Futuna (France)	15,480	200	77	0.28	0.23
128	East Timor	1,134,000	14,874	76	20.70	16.56
129	Myanmar (Burma)	50,020,000	676,578	74	912.87	730.29
130	Bosnia and Herzegovina	3,781,000	51,197	74	69.00	55.20
131	Ethiopia	79,221,000	1,104,300	72	1445.78	1156.63
132	Morocco	32,149,024	446,550	72	586.72	469.38
133	Jordan	6,316,000	89,342	71	115.27	92.21
134	Iraq	30,747,000	438,317	70	561.13	448.91
135	Brunei	400,000	5,765	69	7.30	5.84
136	Kenya	39,802,000	580,367	69	726.39	581.11
137	Swaziland	1,185,000	17,364	68	21.63	17.30
138	Lesotho	2,067,000	30,355	68	37.72	30.18
139	Bulgaria	7,351,234	110,912	66	134.16	107.33
140	Honduras	7,466,000	112,492	66	136.25	109.00
141	Côte d'Ivoire	21,075,000	322,463	65	384.62	307.70
142	Samoa	184,984	2,831	65	3.38	2.70
143	French Polynesia (France)	256,603	4,000	64	4.68	3.75
144	Georgia	4,465,000	69,700	64	81.49	65.19
145	Senegal	12,534,000	196,722	64	228.75	183.00
146	Ireland	4,450,878	70,273	63	81.23	64.98
147	Tunisia	10,327,800	163,610	63	188.48	150.79
148	Uzbekistan	27,488,000	447,400	61	501.66	401.32
149	Montserrat (United Kingdom)	5,900	102	58	0.11	0.09
150	Burkina Faso	15,757,000	274,000	58	287.57	230.05
151	United Arab Emirates	4,599,000	83,600	55	83.93	67.15
152	Mexico	107,550,697	1,958,201	55	1962.80	1570.24
153	Lithuania	3,329,227	65,300	51	60.76	48.61
154	Ecuador	14,681,432	283,561	52	267.94	214.35
155	Tajikistan	6,952,000	143,100	49	126.87	101.50
156	Belarus	9,755,106	207,600	47	178.03	142.42
157	Fiji	849,000	18,274	46	15.49	12.40
158	Tanzania	43,739,000	945,087	46	798.24	638.59
159	Bhutan	2,162,546	47,000	46	39.47	31.57
160	Afghanistan	29,863,010	652,090	46	545.00	436.00
161	Panama	3,454,000	75,517	46	63.04	50.43
162	Iran	74,196,000	1,648,195	45	1354.08	1083.26
163	Montenegro	630,548	14,026	45	11.51	9.21
164	Yemen	23,580,000	527,968	45	430.34	344.27

TABLE 1.6 (Continued)
Countrywise Global Population and Domestic Wastewater Generation

S. No.	Country/Regions	Population	Area (km²)	Density (per km²)	Domestic Demand (MCM per Year)	Wastewater Generation (MCM per Year)
165	Guinea-Bissau	1,611,000	36,125	45	29.40	23.52
166	Nicaragua	5,743,000	130,000	44	104.81	83.85
167	Palau	20,000	459	44	0.37	0.29
168	Eritrea	5,073,000	117,600	43	92.58	74.07
169	Cameroon	19,522,000	475,442	41	356.28	285.02
170	Guinea	10,069,000	245,857	41	183.76	147.01
171	South Africa	49,320,500	1,221,037	40	900.10	720.08
172	Saint Helena (United Kingdom)	4,918	122	40	0.09	0.07
173	Colombia	45,967,392	1,138,914	40	838.90	671.12
174	Djibouti	864,000	23,200	37	15.77	12.61
175	Madagascar	20,653,556	587,041	35	376.93	301.54
176	Faroe Islands (Denmark)	49,006	1,399	35	0.89	0.72
177	Latvia	2,248,961	64,600	35	41.04	32.83
178	Zimbabwe	13,009,530	390,757	33	237.42	189.94
179	United States	311,390,000	9,826,675	32	5682.87	4546.29
180	Liberia	3,476,608	111,369	31	63.45	50.76
181	Venezuela	29,228,598	916,445	32	533.42	426.74
182	Estonia	1,340,021	45,100	30	24.46	19.56
183	Democratic Republic of the Congo	68,692,542	2,344,858	29	1253.64	1002.91
184	Mozambique	22,894,000	801,590	29	417.82	334.25
185	Abkhazia (Georgia; claims independence)	200,000	7,138	28	3.65	2.92
186	Kyrgyzstan	5,482,000	199,900	27	100.05	80.04
187	Laos	6,320,000	236,800	27	115.34	92.27
188	Somaliland (Somalia; claims independence)	3,500,000	137,600	25	63.88	51.10
189	Saint-Pierre and Miquelon (France)	6,125	242	25	0.11	0.09
190	The Bahamas	342,000	13,878	25	6.24	4.99
191	Equatorial Guinea	676,000	28,051	24	12.34	9.87
192	Peru	29,461,933	1,285,216	23	537.68	430.14
193	Brazil	194,718,800	8,514,877	23	3553.62	2842.89
194	Chile	17,241,088	756,096	23	314.65	251.72
195	Sweden	9,366,092	449,964	21	170.93	136.74
196	Uruguay	3,463,197	175,016	20	63.20	50.56
197	Vanuatu	240,000	12,189	20	4.38	3.50
198	Solomon Islands	523,000	28,896	18	9.54	7.64
199	South Ossetia (Georgia; claims independence)	70,000	3,900	18	1.28	1.02
200	Zambia	12,935,000	752,618	17	236.06	188.85
201	New Zealand	4,315,800	270,534	16	78.76	63.01

(*continued*)

TABLE 1.6 (Continued)
Countrywise Global Population and Domestic Wastewater Generation

S. No.	Country/Regions	Population	Area (km²)	Density (per km²)	Domestic Demand (MCM per Year)	Wastewater Generation (MCM per Year)
202	Finland	5,384,580	338,145	16	98.27	78.61
203	Sudan	39,154,490	2,505,813	16	714.57	571.66
204	Paraguay	6,349,000	406,752	16	115.87	92.70
205	Angola	18,498,000	1,246,700	15	337.59	270.07
206	Algeria	34,895,000	2,381,741	15	636.83	509.47
207	Papua New Guinea	6,732,000	462,840	15	122.86	98.29
208	Argentina	40,091,359	2,780,400	14	731.67	585.33
209	Somalia	9,133,000	637,657	14	166.68	133.34
210	Belize	322,100	23,000	14	5.88	4.70
211	Pitcairn Islands (United Kingdom)	67	5	13	0.00	0.00
212	New Caledonia (France)	244,410	18,575	13	4.46	3.57
213	Norway	4,925,155	385,155	13	89.88	71.91
214	Niger	15,290,000	1,267,000	12	279.04	223.23
215	Saudi Arabia	28,146,658	2,149,690	12	513.68	410.94
216	Mali	14,517,176	1,240,192	12	264.94	211.95
217	Republic of the Congo	3,998,904	342,000	12	72.98	58.38
218	Turkmenistan	5,110,000	488,100	10	93.26	74.61
219	Oman	2,845,000	309,500	9.2	51.92	41.54
220	Bolivia	9,879,000	1,098,581	9	180.29	144.23
221	Chad	11,274,106	1,284,000	8.8	205.75	164.60
222	Russia	141,927,297	17,098,242	8.3	2590.17	2072.14
223	Niue (New Zealand)	2,000	260	7.7	0.04	0.03
224	Central African Republic	4,422,000	622,984	7.1	80.70	64.56
225	Kazakhstan	15,776,492	2,724,900	5.8	287.92	230.34
226	Gabon	1,475,000	267,668	5.5	26.92	21.54
227	Libya	6,420,000	1,759,540	3.6	117.17	93.73
228	Guyana	762,000	214,969	3.5	13.91	11.13
229	Canada	33,740,000	9,984,670	3.4	615.76	492.60
230	Botswana	1,950,000	581,730	3.4	35.59	28.47
231	Mauritania	3,291,000	1,025,520	3.2	60.06	48.05
232	Suriname	520,000	163,820	3.2	9.49	7.59
233	Iceland	318,452	103,000	3.1	5.81	4.65
234	Australia	22,729,504	7,682,300	3	414.81	331.85
235	Namibia	2,171,000	824,292	2.6	39.62	31.70
236	French Guiana (France)	187,056	90,000	2.1	3.41	2.73
237	Western Sahara (status disputed)	513,000	266,000	1.9	9.36	7.49
238	Mongolia	2,671,000	1,564,116	1.7	48.75	39.00
239	Falkland Islands (status disputed)	3,140	12,173	0.26	0.06	0.05
240	Greenland (Denmark)	57,000	2,175,600	0.026	1.04	0.83

Source: List of sovereign states and dependent territories by population density, Wikipedia.

1.4.1 AGRICULTURE

Without water, there is no agriculture. It is estimated that 69% of the world's water is being used for the irrigation sector, with 15%–35% of irrigation withdrawals being unsustainable (WBCSD 2009). Approximately 3000 lpcd of water is required to meet the dietary demands of a person. This is a considerable amount, when compared to that required for drinking, which is between 2 and 5 L. Comparing this figure with the IRWR (i.e., Table 1.5), it may be stated that future dietary water demands will be very difficult to meet in many parts of the world. For example, the per capita IRWRs for Pakistan and South Africa are 1016 and 2833, respectively, and are less than the per capita dietary demand of 3000 lpcd. Therefore, to produce food for the 6.5 billion or so people who inhabit the planet today, the amount of water required is 19.5 BCM per day (i.e., 7117.5 BCM per year), which is equivalent to a canal that is 10 m deep, 100 m wide, and 7.1 million km long. This dietary water demand will increase to 27.3 BCM per day (i.e., 9964.5 BCM per year), when the projected world' population for the year 2050 is to be fed.

1.4.2 ENERGY

Regardless of the source of energy generation, large quantities of fresh water are needed. Therefore, recently a term—water-energy nexus—has been coined to emphasize their joint consideration. In a Virginia Tech Study, Younos and Hill (2008) have analyzed 11 types of energy sources, including coal, fuel ethanol, natural gas, and oil, and five power-generating methods, including hydroelectric, fossil fuel thermoelectric, and nuclear methods. Based on their calculations on available governmental reports, they estimated the gallons of water required to generate a British Thermal Unit (BTU). The water-use efficiencies of various energy sources are given in Table 1.7. According to

TABLE 1.7
Water-Use Efficiencies of Various Energy Production Technologies

	Low-Range Efficiency		High-Range Efficiency	
Sources	**L/GJ**	**L/kWh**	**L/GJ**	**L/kWh**
Natural gas	13	0.0466	N/A	N/A
Synfuel–coal gasification	47	0.1708	26	112
Tar sands	65	0.2329	38	164
Oil shale	86	0.3105	50	215
Synfuel–Fisher Tropsch	177	0.6366	60	259
Coal	177	0.6366	164	707
Hydrogen	616	2.2202	243	1047
Liquid natural gas	625	2.2513	N/A	N/A
Petroleum/oil–electric sector	5171	18.6311	2,420	10428
Fuel ethanol	10816	38.9702	29,100	125392
Biodiesel	60326	217.3634	75,000	323175
Hydroelectric	86	0.3105	N/A	N/A
Geothermal	560	2.0184	N/A	N/A
Solar thermoelectric	991	3.5710	270	1163
Fossil fuel thermoelectric	4740	17.0786	2,200	9480
Nuclear	10342	37.2623	5,800	24992

Note: 1 gallon = 3.79 U.S. liters; 1 gallon = 4.546 British liters; 1 BTU = 251.9 calories; 1 million BTUs = 292.8 kWh; 1 million BTUs = 1.055 gigajoules (GJ) the study, the most water-efficient energy sources are natural gas and synthetic fuels produced by coal gasification. The least water-efficient energy sources are fuel ethanol and biodiesel. In terms of power generation, geothermal and hydroelectric energy types use the least amount of water, while nuclear plants use the most (Younos and Hill 2008). For example, electricity production is one of the largest users of water. For example, for a 60-watt incandescent light bulb burning for 12 hours a day for a year in 111 million houses, a power plant would consume about 2.95 BCM of water.

1.4.3 INDUSTRY

It is estimated that 22% of the world's water is used for industries. Major industrial users include hydroelectric dams; thermoelectric power plants, which use water for cooling; ore and oil refineries, which use water in chemical processes; and manufacturing plants, which use water as a solvent. Water withdrawal can be very high for certain industries, but consumption is generally much lower than that of agriculture.

1.4.4 WASTE DISPOSAL

Once water is abstracted for various uses, it gets polluted and disposed into the environment. Wastewater is generally categorized into domestic and industrial. The distribution of wastewater generation from different sectors in the world is shown in Figure 1.9. It can be estimated that about 80% of water is converted into domestic wastewater and needs adequate treatment for final disposal into the environment. However, treated wastewater, if disposed into natural streams, requires additional water to assimilate the pollutants in the river itself. Based on the population and average domestic water use (at the rate of 50 lpcd), estimated domestic water demands and domestic wastewater generation are given in Table 1.6.

Based on these estimates, the global demand for domestic water is approximately 126.3 BCM per year. Due to this consumption, the likely estimate of wastewater generation from households will be 101 BCM per year. It is assumed that every 100 L of wastewater requires 75 L of fresh water for dilution. If 50% of the generated wastewater is treated and reused, then the remaining 50% of the wastewater requires the dilution of water in the amount of 37.9 BCM/year and will be approximately 62.3 BCM/year when the estimation will be based on the projected population of 2050.

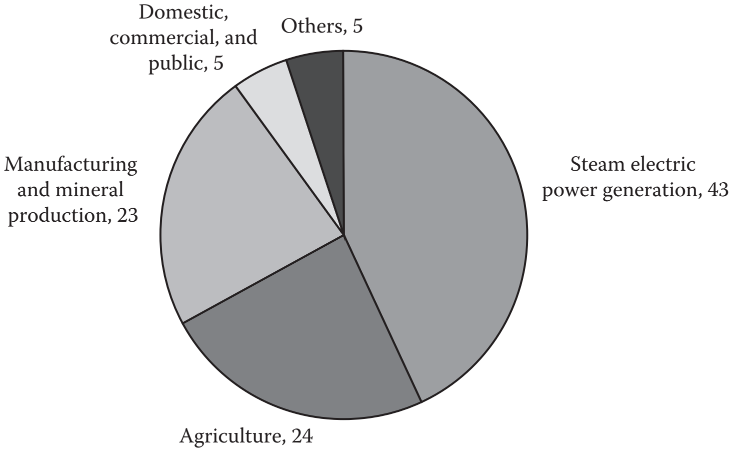

FIGURE 1.9 Percentage distributions of worldwide wastewater generation from different sectors.

1.4.5 Environmental Quality and Management

Water resources and catchment development activities often intercept natural flows in rivers and streams. The interception leads to the impairment of various day-to-day water-based activities and ecosystem functions. To minimize the impairment and maintain the environmental quality of rivers, it is required to allocate a certain percentage of water in the river throughout the year, depending upon the river's natural flow regime, which may be designated as the environmental flow requirement of the river.

Bunn and Arthington (2002) have formulated four basic principles that emphasize the role of flow regime in structuring aquatic life and show the link between flow and ecosystem changes. (i) Flow is a major determinant of physical habitats in rivers and, in turn, is the major determinant of biotic composition. Therefore, river flow modifications eventually lead to changes in the composition and diversity of aquatic communities. (ii) Aquatic species have evolved life history strategies primarily in response to natural flow regimes. Therefore, flow regime alterations can lead to the loss of biodiversity of native species. (iii) Maintenance of natural patterns of longitudinal and lateral connectivity in river floodplains determines the ability of many aquatic species to move between the river and the floodplain or between the main river and its tributaries. The loss of longitudinal and lateral connectivity can lead to the local extinction of species. (iv) The invasion of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. Interbasin water transfer may represent a significant mechanism for the spread of exotic species.

The amount of minimum water to be maintained for a healthy river environment can be decided on the basis of the Tennant method (Tennant 1976). This method establishes stream flow requirements on the basis of a predetermined percentage of mean annual flow (MAF) (i.e., internal renewable surface water resources) and associates aquatic-habitat conditions with different percentages of MAFs. Minimum stream flows for small streams during summer were established by the Tennant method as 40%, 30%, and 10% of MAF, which represent good, fair, and poor habitat conditions, respectively. At 30% MAF, most of the stream substrate is submerged, but at 10% MAF, half or more of the stream substrate can be exposed (Tennant 1976). The 10% MAF value is often used to determine the minimum stream flow requirements in summer. Based on the above discussion, if it is desired to maintain the river system at good habitat condition, then the total volume for environmental water demand in the world may be of the order of 634.5 BCM (i.e., 30% of the total volume of water in the world's rivers, i.e., 2,115 BCM).

1.4.6 Domestic Use

It is estimated that 8% of the world's water is used for domestic purposes. These include drinking water, bathing, cooking, sanitation, and gardening; however, the basic household water requirement is approximately 50 lpcd. Drinking water is water that is of sufficiently high quality that it can be consumed or used without the risk of immediate or long-term harm. Such water is commonly called potable water. In most developed countries, the water supplied to households, commerce, and industry is all of drinking water standard, even though only a very small proportion is actually consumed or used in food preparation. Considering the domestic requirement of 50 lpcd, the annual domestic water use can be estimated to be 118.6 and 166 BCM per year for the current population and the projected population of 2050, respectively.

1.4.7 Availability of Water for Future Use

The amount of water that would be available for future use would depend on the demands and stresses and how these demands are managed, and the overall interaction between the lithosphere, pedosphere, atmosphere, and hydrosphere would be dealt with. Water resources are sensitive to social and environmental variables. Therefore, it is important that a multidisciplinary approach is adopted to develop and manage water resources.

1.5 FOOD SECURITY

The World Food Summit of 1996 defined food security as existing "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life." Commonly, the concept of food security is defined as including both physical and economic access to food that meets people's dietary needs as well as their food preferences. In many countries, health problems related to dietary access are an ever-increasing threat. In fact, malnutrition and food-borne diarrhea are becoming a double burden. Food security is built on three pillars:

- *Food availability*: sufficient quantities of food available on a consistent basis
- *Food access*: having sufficient resources to obtain appropriate foods for a nutritious diet
- *Food use*: appropriate use based on the knowledge of basic nutrition and care, as well as adequate water and sanitation

Food security is a complex sustainable development issue, linked to health through malnutrition, and also to sustainable economic development, environment, and trade.

1.5.1 Requirements to Feed Population

It is assumed that for self-sufficiency, some 900 m^3 of water per person per year has to be provided. Further to this, the FAO in discussion with the CFWA and the World Water Summit (Falkenmark 1997) made the following approximations: a good nutrition level implies 2700 kcal per person per day, with 2300 kcal plant-based nutrition and 400 kcal animal-based nutrition. The production of the former consumes 1 m^3 per 1000 kcal and the latter, 5 m^3 per 1000 kcal, which altogether amounts to 4.3 m^3 per person per day or 1570 m^3 per person per year.

In an arid climate, all of this would have to be provided by blue water (irrigation water). In a humid climate, all may be provided by green water (soil moisture). In a semiarid climate, 50% may be met by green water and 50% by blue water, leading to 800 m^3 per person per year for food self-sufficiency.

An alternative calculation would be the following: for an acceptable plant-based diet, 250 kg per person per year is required (annual per capita grain use in 1990: India, 200 kg per person; China, 300 kg per person) (Brown and Kane 1994).

To feed the projected population of the world by 2050 (i.e., 9.1 billion) while considering changes in dietary patterns, an additional 70% of agricultural production would be required. This dietary pattern shift is toward the consumption of meat, fish, milk, and high-value protein-based food. In financial terminology, to meet the projected demand for the year 2050, over 80 million U.S. dollars need to be invested in the agriculture sector annually. This is an increase of about 50% than what is currently being invested.

In terms of water requirements, to suffice food production for the projected population, an additional 2200 BCM of consumptive water per year will be required (Swedish Assessment). This corresponds to a 50% increase from the current situation. If this requirement is covered by irrigation only, it would involve more than a doubling of all the water withdrawals from rivers and aquifers today, and that would be absolutely unacceptable in view of the degraded river flow regimes and aquatic ecosystems. However, considering the FAO projecting the average diet in the developing countries for 2030–3000 kcal per person per day, an additional consumptive water use of 4200 BCM/year would be required by 2030, assuming that hunger would be altogether eradicated, whereas by the year 2050, the additional water required would go up to 5200 BCM/year.

Besides the above consumptive water need, a study by IWMI suggests that irrigation might not contribute (blue water) more than some 270 BCM/year by 2015 (520 BCM/year by 2030, 725 BCM/year by 2050). Under such circumstances, a question arises as to how the remaining water need will be managed.

1.5.2 Food Wastage

According to the legal definition of waste by the European Commission (EU), food waste is "any food substance, raw or cooked, which is discarded, or intended or required to be discarded." Food wastage may occur at different stages: planting to harvesting; at harvesting; farm-level storages; food processing, packaging, and cooking; postcooking and feeding. Waste magnitudes at different stages are different, though wastage is highest in processing, packaging, and after cooking.

Food waste can have dramatically varied impacts, depending on the amount produced and how it is dealt with. In some countries, the amount of food waste is negligible, and therefore the impact is quite insignificant. However, in developed countries, especially in the United States and the United Kingdom, where food scrap represents around 19% of the waste dumped in landfills, food waste has enormous environmental impact due to the production of methane, a greenhouse gas. A study by Vaughan (2009) reported that the hunger of 1.5 billion people could be alleviated by eradicating food wastage by British consumers and American retailers, food services, and householders, including arable crops such as wheat, maize, and soybean, to produce wasted meat and dairy products. When this fact is converted into water equivalence, it may be remarked that the irrigation water used by the farmers to grow wasted food would be enough for the domestic water requirement for 9 billion people (i.e., 164.25 BCM per year). Further to this, a fresh estimate from the Ministry of Food Processing published that agricultural food of approximately Rs 580 billion gets wasted every year in India. Therefore, the prevention of food wastage is very important to save water, which requires a change in attitude.

1.5.3 Biotechnology

To meet the food demand for the growing population under climatic changes and limited water availability, intensification of agriculture and reliance on irrigation and chemical inputs have led to environmental degradation. Much of Asia faces problems of salinity, pesticide misuse, and degradation of natural resources. The green revolution technologies were useful in the favorable and irrigated environment, but they had little impact on the millions of small landholders living in rainfed and marginal areas where poverty is concentrated. In addition, declining public investments in the agriculture sector across regions have largely affected food production. These factors have been responsible for the decline in annual agricultural growth from an average of 3.3% during 1977–1986 to about 1.5% during 1987–1996.

It means that to meet food demands for the future population (i.e., an increase of 50% in food production by the year 2030), dependence on traditional technology no longer will be helpful. Under such circumstances, it has been required to encourage biotechnology in agriculture to increase production. The advantages of new techniques of modern biotechnology are (i) speedy plant and animal breeding, (ii) possible solutions to previously intractable problems such as drought tolerance, and (iii) the development of new products such as more nutritious food.

Genetically modified (GM) crops have been commercially cultivated since 1996. Over the past years, their worldwide production has continuously increased. It was reported that by the end of the year 2005, GM crops were grown in 21 countries, and the official global area of GM crops totaled 90 million hectares, which amounts to approximately 5% of the area under cultivation.

The contribution of biotechnology toward increasing yields will be realized by decreasing the losses from diseases and pests while minimizing the use of pesticides. Based on several studies, it is expected that agricultural biotechnology will contribute significantly toward poverty reduction and food security through increased productivity, lower production costs and food prices, and improved nutrition (ADB, 2001). Modern plant breeding may help to achieve productivity by introducing resistance to pests and diseases, reduce pesticide use, improve crop tolerance for abiotic stress, improve the nutritional value of some foods, and enhance the durability of products during harvesting and shipping. Biotechnology may offer cost-effective solutions to vitamin and mineral deficiencies by developing rice varieties that contain vitamin A and minerals. Raising productivity could increase small landholders' income, reduce poverty, increase food access, reduce malnutrition, and improve livelihoods of the poor. Besides the above advantages, the long-term impact of genetically improved foods on human health and the environment is not known; that will require monitoring and further research.

1.5.4 Climatic Extremes: Floods and Droughts

Agriculture is highly sensitive to climate variability and weather extremes, such as droughts, floods, and severe storms. The forces that shape the climate are also critical to farm productivity. Human activities have already changed the atmospheric characteristics such as temperature, rainfall, evapotranspiration, levels of CO_2, and ground-level ozone. The scientific community expects such trends to continue. The increased potential for droughts, floods, and heat waves will pose challenges for farmers. Additionally, due to the enduring climatic changes, available water supply and soil moisture could not make it feasible to continue crop production in certain regions.

The coastal flooding will further reduce the amount of land available for agriculture. Due to climatic extremes (www.who.int/globalchange/en/), the natural disaster impacts have been increasing in different geographical regions (Table 1.8). Based on origin, the distribution of natural disasters (Table 1.9) is shown in Figure 1.10, which shows that natural disasters caused by hydrometeorology are more than the others (Source: International Disaster Database: www.em-dat.net). The trend associated with hydrometeorological disasters is increasing in nature.

TABLE 1.8
Number of Climatic Extremes and People Affected

	1980s			1990s		
Regions	**Events**	**Killed (1000 People)**	**Affected (1000 People)**	**Events**	**Killed (1000 People)**	**Affected (1000 People)**
Africa	243	417	137.8	247	10	104.3
Eastern Europe	66	2	0.1	150	5	12.4
Eastern Mediterranean	94	162	17.8	139	14	36.1
Latin America and Caribbean	265	12	54.1	248	59	30.7
Southeast Asia	242	54	850.5	286	458	427.4
Western Pacific	375	36	273.1	381	48	1199.8
Developed countries	563	10	2.8	577	6	40.8
Total	*1848*	*692*	*1336*	*2078*	*601*	*1851*

Source: United Nations International Strategy for Disaster Reduction, www.unisdr.org/disaster-statistics/.

TABLE 1.9
Distribution of Natural Disasters by Origin

Nature/Origin	**1900–1909**	**1910–1919**	**1920–1929**	**1930–1939**	**1940–1949**	**1950–1959**	**1960–1969**	**1970–1979**	**1980–1989**	**1990–1999**	**2000–2005**	**Total**
Total	73	107	99	112	176	294	588	964	1900	2720	2788	9821
Hydrometeorological	28	72	56	72	120	232	463	776	1498	2034	2135	7486
Geological	40	28	33	37	52	60	88	124	232	325	233	1252
Biological	5	7	10	3	4	2	37	64	170	361	420	1083

Source: Centre for Research on the Epidemiology of Disasters, EM-DAT: The International Disaster Database, www.em-dat.net.

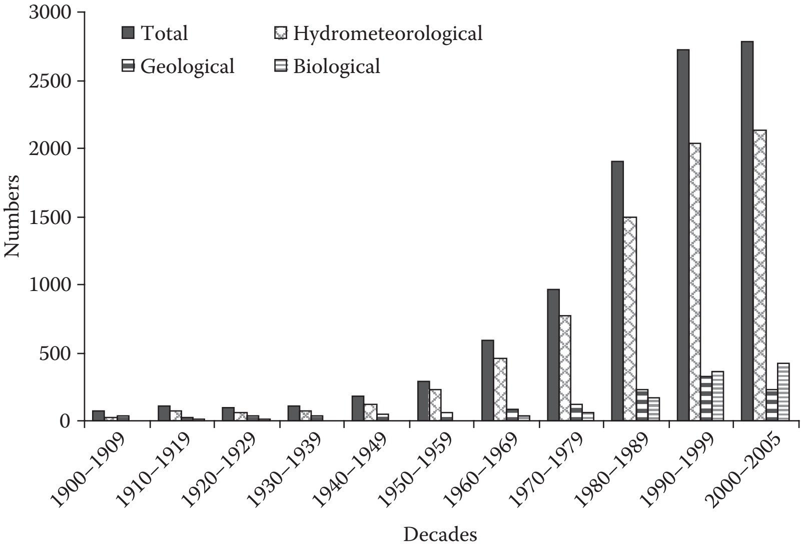

FIGURE 1.10 Distribution of natural disasters by origin. (From Centre for Research on the Epidemiology of Disasters, EM-DAT: The International Disaster Database, www.emdat.be.)

1.5.5 Conflicts and Wars

For centuries, wars and conflicts have been tied to the protection of water resources. With the risk of water shortages around the world becoming more and more of an issue, water has become the fuel of certain conflicts in many regions around the world. Many regions around the world deal with shortages of water, leading to interstate and intercountry disputes. Globally, over 200 water bodies are shared by two or more countries or areas. A few examples are as follows:

i. *The Middle East*: Middle East conflicts are usually tied to religious issues or oil, but water has become a major factor in recent disputes. This water dispute arises from the overuse and political territorial uses resulting from the disagreement in water distribution of the Jordan and the Tigris–Euphrates River Basins. The Jordan River Basin includes parts of Lebanon, Syria, Israel, Jordan, and the West Bank. However, Turkey, Syria, and Iran are the countries having water conflicts due to the Tigris–Euphrates Basin.

ii. *Africa*: In many parts of Africa, the water shortage has become part of daily life. Water conflicts due to sharing of the Nile River water between Uganda, Sudan, and Egypt have been seen but prevented through political will by signing a sharing agreement.

iii. *Asia*: In India and China, water shortages pose both social and economic threats. Throughout India, Pakistan, Nepal, and Bangladesh, water shortages are increasingly triggering conflict. The Indus River Basin and the Ganga River Basin are the major areas of water conflicts between India and Pakistan and between India and Bangladesh, respectively. In India herself, there are interstate disputes due to water sharing of the Yamuna River water and the Cauvery River water.

Generally, it is stated that the third world war will be fought over water.

1.6 WATER AND WATERSHED MANAGEMENT

Starting from the availability of fresh water in terms of total renewable water resources (TRWR), the impact of population growth and climate change, and environmental protection, water has become a critical issue that will lead to future conflicts and wars among various nations and regions. Therefore, by now it is of prime importance to think about how to deal with this issue of future water requirement to meet the various needs. The only way that seems to resolve this issue is watershed management, and the first step will be the inventory of natural resources at the watershed scale.

Watershed management is the process of creating and implementing plans, programs, and projects to sustain and enhance watershed functions that affect the plant, animal, and human communities within a watershed boundary. Watershed management includes the optimal utilization and planning of available natural resources along with the management of water supply, water quality, drainage, storm water runoff, water rights, etc.

For sustainable watershed management, there should be causal linkages between the geophysical science, society, ecology, and economics. The three main components of watershed management are (i) land management, (ii) water management, and (iii) biomass management. The land management is determined by the land characteristics such as terrain, slope, formation, depth, texture, moisture, infiltration rate, and soil capability. Altogether, these factors can be termed as land capabilities. The land management interventions can be categorized as structural, vegetative, production, and protection measures.

Mechanical conservation measures may become necessary in watershed management in the initial stages. Structural measures include interventions such as contour bunds, stone bunds, earthen bunds, graded bunds, compartmental bunds, contour terrace walls, contour trenches, bench terracing, broad based terraces, centripetal terraces, field bunds, channel walls, stream bank stabilization, check dams, etc. Watersheds may contain natural ecosystems such as grasslands, wetlands, mangroves, marshes, and water bodies. All these ecosystems have a specific role in nature. Vegetative measures include vegetative cover, plant cover, mulching, vegetative hedges, grass land management, fencing, agroforestry, etc. The production measures include interventions aimed at increasing the productivity of land, such as mixed cropping, strip cropping, cover cropping, crop rotations, cultivation of shrubs and herbs, contour cultivation conservation tillage, land leveling, use of improved variety of seeds, horticulture, etc. Protective measures, such as landslide control, gully plugging, runoff collection, and so on, can also be adopted. Adoption of all the interventions mentioned above should be done strictly in accordance with the characteristics of the land taken for management.

Water characteristics such as inflows (precipitation, surface water inflow, groundwater inflow), water use (evaporation, evapotranspiration, irrigation, drinking water), outflows (surface water outflow, groundwater outflow), and storage (surface storage, groundwater storage, root zone storage) are the principal factors to be taken care of in sustainable water management. The broad interventions for water management are rainwater harvesting, groundwater recharge, maintenance of water balance, preventing water pollution, economic use of water, preventing various losses, etc.

Rainwater harvesting forms the major component of water management. The rainwater collected can be recharged into the ground. Rooftop water harvesting, diversion of perennial springs and streams into storage structures, farm ponds, and so on, are the methods widely used for rainwater harvesting. Some simple and cost-effective rainwater-harvesting structures are percolation pits/tanks, recharge trenches/rain pits, recharge wells, ferro-cement tanks, farm ponds, V ditch, bench terracing, etc. The economic use of water and avoidance of affluence in the use of water at individual and community levels may be the major concern for water management in the years to come.

Major intervention areas for biomass management include eco-preservation, biomass regeneration, forest management and conservation, plant protection and social forestry, increased productivity of animals, income and employment generation activities, coordination of health and sanitation programs, better living standards for people, eco-friendly lifestyle of people, formation of a learning community, etc.

Besides the above three components of watershed management, public participation and collective action are critical ingredients for sustainable management. Sustainability, equity, and participation are the three basic elements of participatory watershed management. Sustainability involves the conservation and enhancement of the primary productivity of the ecosystem, the main components of which are land, water, and biomass. Equity has to be seen in terms of creating an equitable access to livelihood resources for the watershed community. Participatory watershed management attempts to ensure the sustainability of the ecological, economic, and social exchanges taking place in the watershed territory. This includes natural resource exchange, which is the conventional watershed management, and participatory watershed management additionally considers the economic, political, and cultural exchanges.

1.6.1 WATER ALLOCATION AND VALUING/PRICING

For sustainable water resources management, a few important statements need to be carefully understood:

i. Dublin Statement on Water and Sustainable Development (ICWE 1992):
"Principle No. 4: Water has an economic value in all its competing uses and should be recognized as an economic good. Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources."

ii. Agenda 21, Chapter 18 (UNCED 1992):
"Water should be regarded as a finite resource having an economic value with significant social and economic implications regarding the importance of meeting basic needs."

iii. Ministerial Declaration of the 2nd World Water Forum (World Water Council 2000):
"To manage water in a way that reflects its economic, social, environmental and cultural values for all its uses, and to move towards pricing water services to reflect the cost of their provision. This approach should take account of the need for equity and the basic needs of the poor and the vulnerable."

iv. Ministerial Declaration of the 3rd World Water Forum (World Water Council 2003):
"Funds should be raised by adopting cost recovery approaches which suit local climatic, environmental and social conditions and the 'polluter-pays' principle, with due consideration to the poor. All sources of financing, both public and private, national and international, must be mobilized and used in the most efficient and effective way."

The focus on economic efficiency as the primary objective in the development and allocation of water resources is because of its importance as a social objective: efficiency values having viable meaning in resolving conflicts and assessing the opportunity costs of pursuing alternative uses (Young 1996). Although economically efficient allocation of irrigation water is rarely attained in practice, the analysis of economic efficiency provides a useful point of reference for understanding the causes of inefficient allocation and mechanisms for improving the overall economic performance of irrigated production.

Economically efficient allocation of water is desirable to the extent that it maximizes the welfare that society obtains from available water resources. Welfare in this context refers to the economic well-being of society and is determined by the aggregate well-being of its individual citizens. Economically efficient allocation maximizes the value of water across all sectors of the economy. This is achieved through the allocation of water to uses that are of high value to society and away from uses with low value. Efficient allocation occurs in a competitive, freely functioning market when supply is in equilibrium with demand (Tsur and Dinar 1997).

TABLE 1.10
Policy Measures Relevant to Resource Management

Conditions	Public Sector		Private Sector	
Poverty rights	Least-developed country	Developing country	Least-developed country	Developing country
Pricing	Price = Marginal cost Price = Marginal social cost	Price = Marginal social cost	Price = Marginal social cost	Price = Marginal social cost
Quantity trading			Possible emissions and resource quota trading	Emissions and resource quota trading
Command and control	Environmental quality objectives	Environmental quality objectives	Environmental quality objectives	Environmental quality objectives
Investment policy	Cost–benefit analysis	Cost–benefit analysis	Environmental impact assessment	Environmental impact assessment

As indicated above, economic efficiency and equity are important considerations in the allocation of water. Greater efficiency is required in the face of increasing water scarcity, and equity is a concern because of the importance of water to the livelihoods and well-being of rural communities in particular. It is possible to derive a broad classification of policy measures that are relevant to managing resources within the boundaries of a nation. The measures include the redefinition of property rights and investment policies.

One thing to be kept in mind is that many of the large public irrigation schemes that were promoted as part of the green revolution, particularly in Asia, were designed to target poor rural communities and as such were never oriented to maximize economic output, but instead to guarantee production of food staples (Plusquellec 2002).

The proper pricing of inputs (such as raw water) and outputs (such as agricultural irrigation products) can be viewed as a form of property right designation, while command and control measures are also means of defining property rights or modifying existing ones (FAO 2004). Table 1.10 shows the various generic types of policy measures. Once a regime of property rights has been established, the proper pricing of a resource requires that it be priced at least at marginal private costs and preferably at marginal social cost (especially in the longer term and where output prices are below the private production costs). As pricing of water affects the allocation decisions of those with competing wants, then by correctly pricing water, efficient allocation of water is achieved. However, the standard economic efficiency (marginal) cost pricing result is sometimes problematic as regards the specification of production technology. In the water supply sector, inputs to production are often not perfectly divisible. Investments often require large lumps of capital (e.g., for dams and reservoirs). In such cases, marginal cost pricing to achieve economic efficiency requires some form of intervention (Sherman 1989). Table 1.10 lists quantity-based measures as a separate policy option, although they have similar effects on the price-based measures. Finally, investment policy, which is most usually characterized in terms of cost–benefit analysis, is applicable to all public-sector operations (although environmental impact assessments are employed most widely in assessing private-sector environmental impacts).

Water allocation systems differ in the extent to which they address efficiency and equity in objectives. The various systems can be compared according to several criteria (Dinar et al. 1997; Howe et al. 1986; Winpenny 1994):

- *Flexibility in allocation of supplies*: allocation requires flexibility such that supplies can be shifted between uses and sectors, as demand changes, so as to achieve efficiency.

- *Security of tenure for users*: established users require security of tenure if they are to be expected to take the necessary measures to use the resource efficiently. Although this may conflict with flexibility, problems should not arise if sufficient water reserves are available to meet the unexpected demands.
- *Payment of real opportunity costs of water by users*: users should pay the real opportunity costs of their use, so that other demand or external effects are internalized.
- *Predictability of the allocation outcome*: in order to achieve the best allocation and minimize uncertainty, the outcome of the allocation process needs to be predictable.
- *Equity in the allocation process*: users should perceive the allocation process to be equitable.
- *Political and public acceptability*: the allocation should serve the various political and public values and objectives, thereby making it acceptable to the groups in society.
- *Efficacy in achieving desired policy goals*: the form of allocation should change an existing undesirable situation toward one where the desired policy goals are achieved.
- Administrative feasibility and sustainability: the allocation mechanism must be practicable, adaptable, and allow an increasing effect of policy.

Water allocation systems range from government-controlled to market-led systems, and combinations of the two. The prevailing institutional frameworks (including laws, regulations, and organizations) and the water resources infrastructure (Dinar et al., 1997) influence the precise nature of allocation systems. However, they commonly fall into one of only a small number of categories: public allocation, market-based allocation, and user-based allocation.

1.6.2 WATER CONSERVATION

Water conservation refers to the process of reducing the usage of water and recycling of wastewater for different purposes such as cleaning, manufacturing, construction, agricultural irrigation, and parks. The goal of water conservation efforts includes sustainability, energy conservation, and habitat conservation. The important components of water conservation are water reuse, water recycling, and water-use efficiency.

1.6.3 WATER RECYCLING AND REUSE

Looking into the global water scarcity, wastewater recycling and reuse may be one of the good water conservative options. The motivational factors for wastewater recycle/reuse may include the following:

- Opportunities to augment limited primary water sources
- Prevention of excessive diversion of water from alternative uses, including the natural environment
- Possibilities to manage in situ water sources
- Minimization of infrastructure costs, including total treatment and discharge costs
- Reduction and elimination of discharges of wastewater (treated or untreated) into the receiving environment
- Scope to overcome political, community, and institutional constraints

Reuse of wastewater can be a supplementary source to existing water sources, especially in arid/semiarid climatic regions. Most large-scale reuse schemes are in Israel, South Africa, and arid areas of the United States, where alternative sources of water are limited. This option will be beneficial even in the regions where rainfall is adequate but water shortage is caused due to the spatial and temporal variability. For example, Florida, in the United States, is not a dry area, has limited options for water storage, and suffers from water shortages during dry spells. For this reason, wastewater reuse schemes form an important supplement to the water resource of this region.

1.6.4 WATER-USE EFFICIENCY

Water-use efficiency is a tool of water conservation that results in more efficient water use and thus reduces water demand. The value and cost-effectiveness of a water efficiency measure must be evaluated in relation to its effects on the use and cost of other natural resources (e.g., energy and chemicals).

1.7 SUMMARY AND CONCLUSION

The availability of good quality water will vary from one region to another. A multidisciplinary approach will be required to determine accurately the water availability. In this chapter, a holistic approach has been considered to develop a wide and basic understanding of the different issues related to water resources and food security. For water resources, a general baseline in terms of the hydrologic cycle and renewable water resources has been described, followed by the possible impacts on the availability and uses of water due to climate change, population growth, environmental pollution, etc. Based on the consequences, including spatiotemporal variability, it may be stated that the availability of good quality water will be a great challenge in the near future for the livelihood and the environment. Under such circumstances, it will be important to think over each and every drop of water being used and wasted. There should be a proper accounting of water consumption for suppliers and users as well. Based on the aforesaid discussions, the following concluding thoughts can be suggested to meet future demands:

i. Agriculture: It is the highest water consumer, and therefore, it should be optimized on a spatial basis through proper cropping patterns, adequate irrigation methods, adequate crop variety, organic farming, minimizing the conveyance losses, etc. These are the practices at watershed level management. However, for global action, in addition to these, virtual water transfer should be encouraged and brought into the national water and agricultural policy.
ii. Changes in lifestyle and food habits may reduce water consumption. This will require shifting the food habit from nonvegetarian to vegetarian.
iii. Food wastage: Food wastage can save several billions of water per year.
iv. Minimization of losses incurred in domestic water supply.
v. Wastewater management: The disposal of wastewater, either treated or untreated, into rivers must be minimized, because approximately 50%–75% of fresh water is needed for dilution. Wastewater should be treated using such a technology that it can be completely reused for various purposes such as irrigation, construction, and reserved parks.
vi. A sustainable watershed management framework needs to be developed and followed under policy with proper enforcements. It should consider the inventory of all natural resources including land-use capability and water resources availability, livestock, socioeconomics, and environmental health.
vii. For the success of any good water resource or watershed management plan, public participation is important. The first step to involve the public into the plan is by adequate accounting of water consumption and wastewater generation; social and environmental impacts of their water use should be quantified and billed. Misuse of water and the resultant environmental damage should be treated as an offense.
viii. There should be population control in urban centers especially located near river banks to prevent river pollution.
ix. Among the above, the most important constraint is the continuous population growth. How to control it will be a major challenge.

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2 Soil Water and Agronomic Production

Rattan Lal

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2.1 INTRODUCTION

Ever since the evolution of *Homo sapiens*, the human population touched 1 billion by ~1800 AD. The population touched 2 billion by 1925, 3 billion by 1960, 4 billion by 1974, 5 billion by 1987, 6 billion by 1999, and 7 billion by 2011 (UN 2011). The population is projected to touch 8 billion by 2028 and 9 billion by 2054 and may stabilize at 10 billion by 2100 and beyond. Despite the exponential growth in the human population, earth's natural resources are either fixed or dwindling. For example, only 2.5% of the earth's total water reserve is fresh water (Figure 2.1). Freshwater ecosystems cover <1% of the earth's surface (Johnson et al. 2001). There is no alternative to water, it has many competing uses, and it is a scarce commodity. As much as 40% of the world's population and several ecosystems are already vulnerable to water scarcity (Oki and Kanae 2006), and the adverse effects of scarcity will be exacerbated by an increase in the population and its numerous demands (Pfister et al. 2011).

Soil is an important reservoir of fresh water (Table 2.1), and the growth of all terrestrial plants and soil biota depends on its availability and quality. The principal source of soil water is the precipitation and infiltration or transfer into the soil from the soil–atmosphere interphase. Soil water is lost by evaporation, transpiration, and deep seepage or percolation. Soil water storage and its judicious use can reduce the adverse effects of water scarcity, because soil water in the root zone is the essence of all terrestrial life.

Soil water, also called green water (Rockström et al. 2009), is composed of only a fraction of renewable freshwater resources (17×10^3 km^3; Table 2.1). Green water is the soil water held in the unsaturated zone, is formed by precipitation, and is available for plants. Green water is strategically important in relation to international commodity trade (Aldaya et al. 2010). Because of its

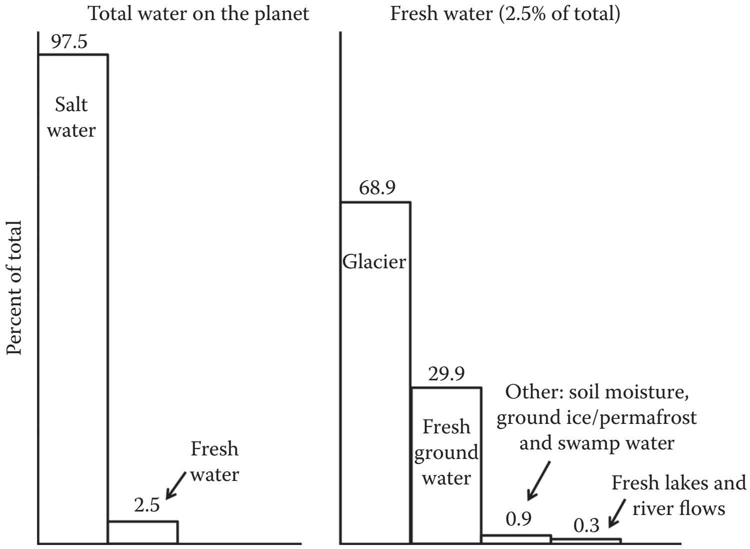

FIGURE 2.1 Distribution of global water. (Adapted from Shiklomanov, I., In *Water in Crisis: A Guide to Word's Fresh Water Resources*, p. 473, Oxford University Press, Oxford, UK, 1993.)

low opportunity cost, the effective and efficient use of green water for crop production has comparatively less environmental externalities than the use of blue water for supplemental irrigation. In this context, therefore, blue water refers to the water in lakes, rivers, and wetlands, which can be withdrawn for irrigation. Thus, irrigated land receives both green and blue water, but rainfed land depends only on green water (Falkenmark and Rockström 2006; Hoff et al.

TABLE 2.1
Terrestrial Water Balance

Parameter		Amount
I	Reservoirs (10^3 km^3)	
	Ocean	1,338,000
	Glacier and snow	24,064
	Permafrost	300
	Lake	175
	Wetland	17
	Soil moisture	17
	Biological water	1.0
	Water vapor overland	3.0
	Water vapor over sea	10.0
II	Fluxes (10^3 km^3/year)	
	Precipitation over ocean	391
	Total terrestrial precipitation	111
	Evaporation over ocean	436.5
	Total terrestrial evapotranspiration	65.5
	Total river flow	45.5
	(i) Surface runoff	15.3
	(ii) Subsurface runoff	30.2

Source: Adapted from Oki, T. and Kanae, S., *Science*, 313, 1068–1072, 2006.

2010). By comparison, gray water is urban and industrial water (polluted/contaminated), which can be reused for irrigation following some treatment. Virtual water is the water traded among nations (regions) through trade of food. It refers to the water required in the production of crops. Thus, the exchange of water through the trade of agricultural produce involves the virtual water trade. The virtual water content of crops grown in the Indo-Gangetic Plains of northern India is estimated at 745–9405 m^3/Mg for wheat and 2502–9562 m^3/Mg for rice (Kumar and Jain 2011). At present, the global virtual water trade is ~1000 km^3/year. Thus, the total water use within a country is a combination of the national water withdrawn/consumed plus the traded virtual water.

Despite a limited supply of renewable freshwater resources, human demand has increased drastically. During the twentieth century, global water withdrawal increased by a factor of 6.8 from 579 km^3/year in 1900 to 3927 km^3/year in 2000 (Gleick 2003; Table 2.2). Irrigation of agricultural lands is the major consumer of freshwater withdrawal, 2504 km^3/year out of 3765 km^3/year in 1995 (~70%, Table 2.2), and the demand is projected to double by 2050 (Tilman et al. 2002). The demand for water will also increase because of the emphasis on biofuels (Melillo et al. 2009). Agriculture uses 1300 m^3 capita/year to produce an adequate diet (Falkenmark and Rockström 2004). Therefore, the sustainable management of soil water (precipitation + irrigation) is critical to enhancing agronomic production and saving water for other competing but essential uses (i.e., industry, domestic, and recreation).

Similar to water, soil resources of good quality are also limited. Both the per capita renewable fresh water and the per capita arable land area are declining with the increase in the population and the demands caused by growing affluence and standards of living. Some 1020 million people face transit and chronic hunger (FAO 2009), and 3.5 billion additional people must be fed within the next five decades (Borlaug 2007). The sustainable management of soils and green water is essential to advancing food security.

Therefore, the objective of this chapter is to describe the state-of-the-world's water resources that are usable for agriculture, to discuss the technological options for sustainable management under an uncertain climate and degrading and dwindling soils, and to outline a technological option for enhancing soil/green water availability for increasing agronomic production to meet the food demands of the increasing population.

TABLE 2.2
World Water Withdrawal and Consumption

Year	Global Water Withdrawal (km^3/year)	Global Water Consumption (km^3/year)	Irrigated Area (10^6 ha)	Global Irrigated Water Withdrawal (km^3/year)	Global Irrigation Water Consumption (km^3/year)
1900	579	331	47.3	513	321
1940	1088	617	76.0	895	586
1950	1382	768	101.0	1080	722
1960	1968	1086	138.8	1481	1005
1970	2526	1341	167.7	1743	1186
1980	3175	1686	209.3	2112	1445
1990	3633	1982	245.2	2425	1691
1995	3765	2074	263.7	2504	1753
2000	3927	2329	276.3	—	—
2010	4323	2501	—	—	—

Source: Modified from Scanlon, B.R., et al., *Water Res.*, 43, 1, 2007.

2.2 AGRONOMIC PRODUCTION AND WATER DEMAND

The increase in agricultural production since 1960 is among the world's greatest success stories. The production of foodgrains increased from 660 million ton (Mt) in 1960 to >2400 Mt in 2010, by a factor of 3.7. Indeed, the growth rate of agronomic/food production surpassed that of the world's population, which more than doubled from 3 billion in 1960 to 7 billion in 2011. In the United States, the grain yields of corn (*Zea mays*) (Figure 2.2), soybean (*Glycine max*) (Figure 2.3), wheat (*Triticum aestivum*) (Figure 2.4), and rice (*Oryza sativa*) (Figure 2.5) increased linearly between 1960 and 2010. A similar increase in the yields of all cereals happened on a global scale (Figure 2.6). Consequently, global food grain production increased drastically over this period (Figure 2.7). This remarkable success, which saved hundreds of millions from starvation, was partly due to the expansion of cropland area equipped with irrigation facilities. Between 1900 and 2000, the agricultural area increased from 813 to 1382 million hectares (Mha) for cropland and from 2118 to 3426 Mha for pastureland. The use of N fertilizer increased from 11.6 Mt in 1950 to 104 Mt in 2008 (Table 2.3). Similar to fertilizer use, the irrigated land area increased from 47.3 Mha in 1900 to 276.3 Mha in 2000 (Table 2.2). Consequently, global irrigated water withdrawal increased by a factor of 4.9 from 513 km^3/year in 1900 to 2504 km^3/year in 1995. Global irrigation water consumption increased by a factor of 5.5 from 321 km^3/year in 1900 to 1753 km^3/year in 1995 (Table 2.2). Because of the increasing demand from industry and urbanization, the supply of renewable fresh water will decrease between 1985 and 2025 (Table 2.4; Rockström et al. 2009). About 40% of the total food production relies on supplemental irrigation (Vico and Porporato 2011), because the green water stored in the effective rooting depth for rainfed/dry farming is inadequate. The potential for expanding irrigation is severely constrained in arid, semiarid, and semihumid regions. Therefore, enhancing soil water storage and its judicious management to increase crop yield per drop are crucial to enhancing agronomic production and achieving global food security.

2.3 REGIONAL WATER BALANCE AND WATER PRODUCTIVITY

The water balances for different biomes are shown in Table 2.5 (Shen and Chen 2010). Runoff (blue water), which is expressed as a percentage of precipitation, is 7% for arid, 9% for semiarid, 20% for

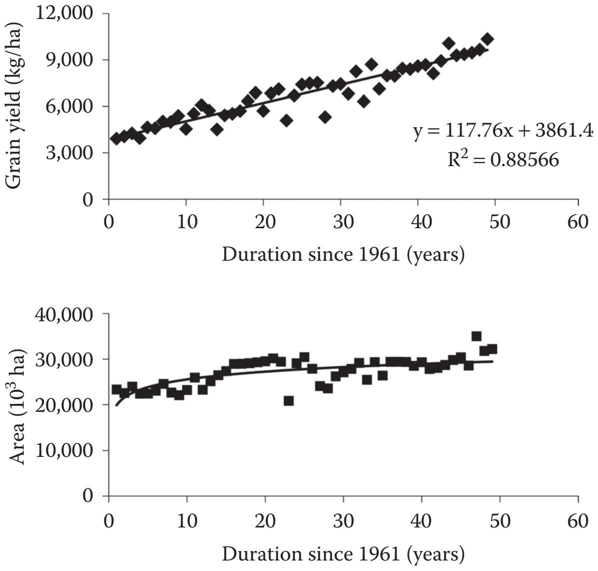

FIGURE 2.2 Change in cultivated area and grain yield of maize in the United States between 1961 and 2010. (Redrawn from USDA. Crop acreage and yields. 2010. http://www.usda.gov/wps/portal/usda/usdahome?parentnav=AGRICULTURE&navid=CROP_PRODUCTION&.)

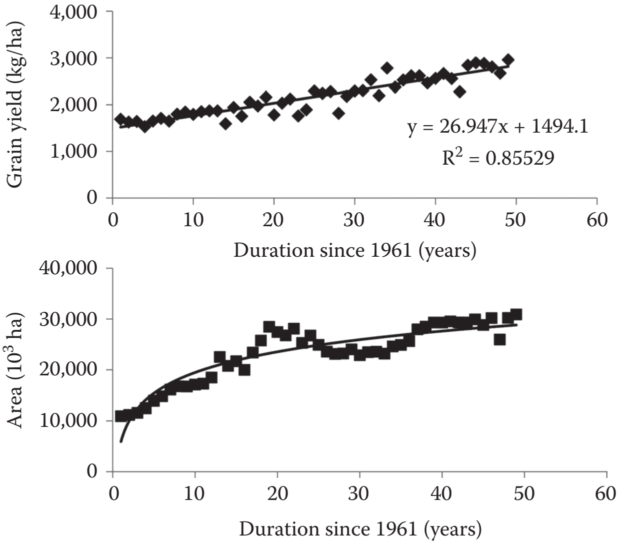

FIGURE 2.3 Change in cultivated area and grain yield of soybean in the United States between 1961 and 2010. (Redrawn from USDA. Crop acreage and yields. 2010. http://www.usda.gov/wps/portal/usda/usdahome?parentnav=AGRICULTURE&navid=CROP_PRODUCTION&.)

semihumid, and 37% for humid regions. Losses due to evaporation are also high in arid and semiarid regions. Thus, the potential for using runoff (blue water) for irrigation is rather low in arid and semiarid regions. There is a severe decline in the groundwater level in the Indo-Gangetic Plains in South Asia (see Chapter 6), China (Cominelli et al. 2009; Fang et al. 2010), and the Ogalalla Aquifer in the United States (see Chapter 4). Even in regions where runoff (blue water) can be used for irrigation, capital investment is prohibitively high for resource-poor, small landholders (Revelle 1976). Thus,

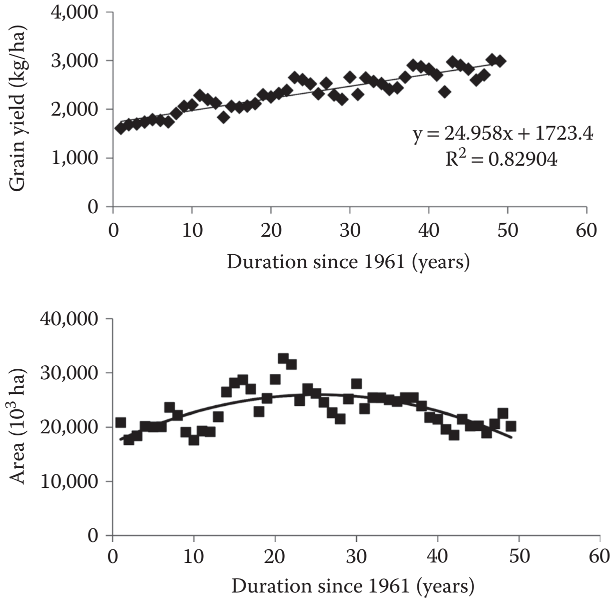

FIGURE 2.4 Change in cultivated area and grain yield of wheat in the United States between 1961 and 2010. (Redrawn from USDA. Crop acreage and yields. 2010. http://www.usda.gov/wps/portal/usda/usdahome?parentnav=AGRICULTURE&navid=CROP_PRODUCTION&.)

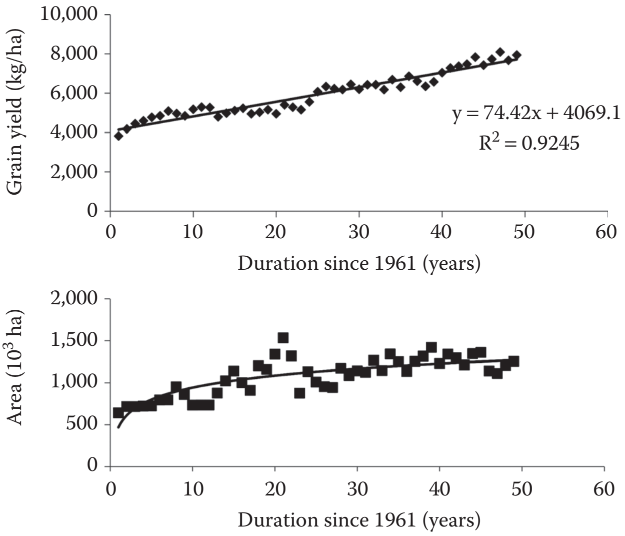

FIGURE 2.5 Change in cultivated area and grain yield of rice in the United States between 1961 and 2010. (Redrawn from USDA. Crop acreage and yields. 2010. http://www.usda.gov/wps/portal/usda/usdahome?parentnav=AGRICULTURE&navid=CROP_PRODUCTION&.)

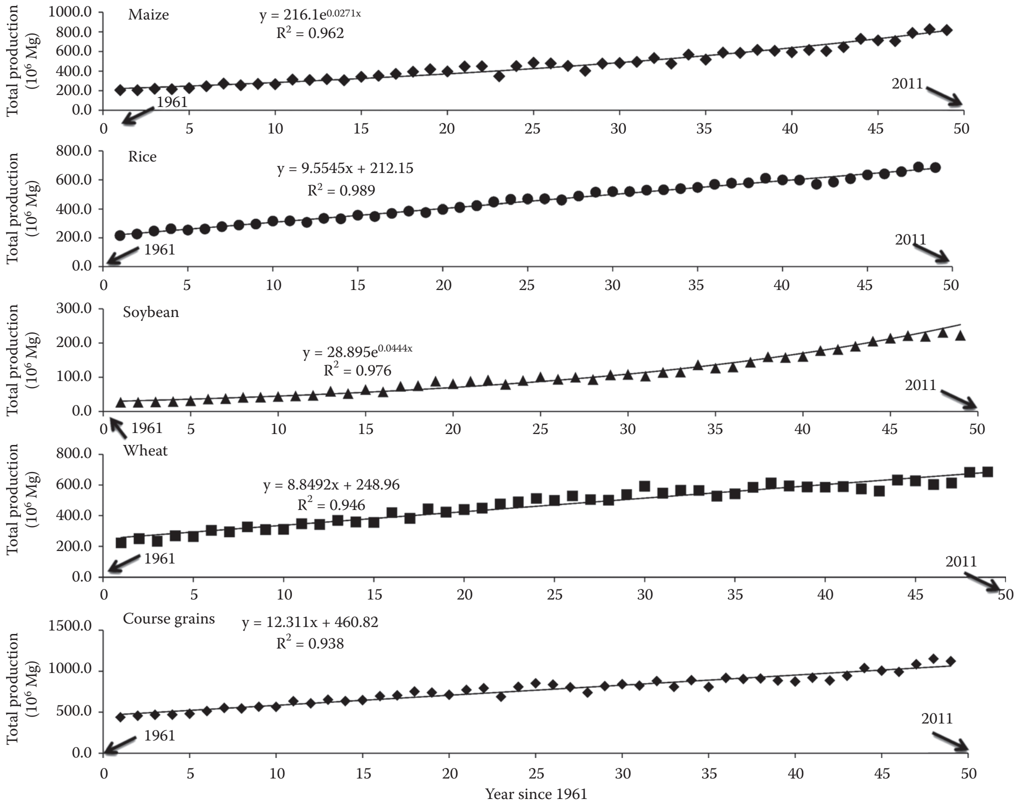

FIGURE 2.6 Changes in global grain production of principal grain crops. (Redrawn from FAOSTAT. Crop production. 2010. http://faostat.fao.org/site/567/desktopDefault.aspx?PageID=567#ancor.)

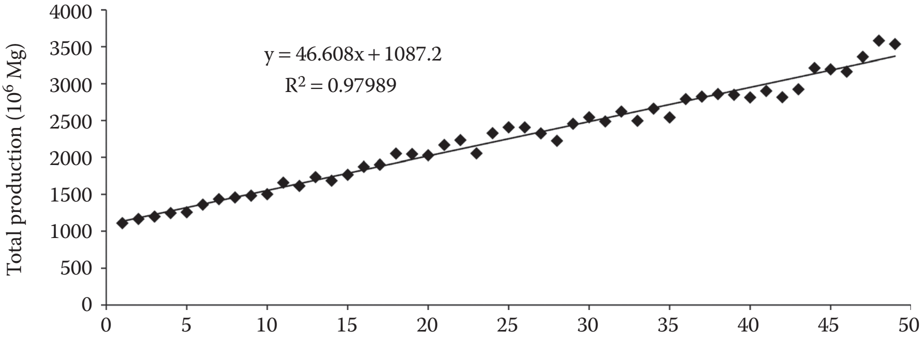

FIGURE 2.7 Change in total grain production in the world. (Redrawn from FAO. FAOSTAT. 2011. http://faostat.fao.org/site/567/desktopdefault.aspx?PageID=567#ancor. Accessed August 1, 2011.)

the rate of future expansion of irrigation will be slower (Plusquellec 2002). Therefore, the strategy is to produce more from less and more crop per drop of renewable fresh water consumed in agricultural lands. This strategy has also been termed "greening the global water system" (Hoff et al. 2010).

The effective use of water for agricultural production is measured by water-use efficiency (WUE) and water productivity (WP). The term, "water-use efficiency," used by irrigation specialists, assesses the effectiveness of the water delivery to crops as affected by losses during delivery (i.e., seepage and evaporation). Others have defined WUE as the ratio of the amount of agricultural output to the input or flux of water used in its production (Moore et al. 2011). However, a wide range of variables are used as the denominators in computing the ratio (Perry et al. 2009), including precipitation, irrigation, precipitation plus irrigation, evapotranspiration, and transpiration. Similarly, a wide range of variables are used as the numerators, including photosynthetic rates, shoot biomass, grain yield, income, and profit. (Peden et al. 2007).

In this chapter, however, the term WP is used. Yet, WP also includes the benefits and costs of water use (Molden et al. 2010). There are two types of WP: (i) physical WP is the ratio of

TABLE 2.3
Global Land Use

Year	Cropland (10^6 ha)	Pastureland (10^6 ha)	Nitrogen Fertilizer Use (10^6 Mg)	Total Fertilizer Use (10^6 Mg)
1700	265	524	—	—
1750	321	697	—	—
1800	402	942	—	—
1850	537	1955	—	—
1900	813	2118	—	—
1950	1230	2930	—	—
1960	1361	3208	11.6	31.1
1970	1405	3276	31.8	69.3
1980	1444	3357	60.8	116.7
1990	1478	3450	77.2	137.8
2000	1382	3426	—	135.2
2008	1380	3357	103.8	—

Source: Modified from Scanlon, B.R., et al., *Water Res.*, 43, 1, 2007; FAO. FAOSTAT. 2011. http://faostat.fao.org/site/567/desktopdefault.aspx?PageID=567#ancor. Accessed August 1, 2011; IFDC. Global and regional data on fertilizer production and consumption 1961/62–2002/3. Muscle Shoals, AL, 2004.

TABLE 2.4
Present and Future Demands of Water Resources for Irrigation

	Population		Water Supply (km³/year)	
Region	**1985**	**2025**	**1985**	**2025**
Africa	543	1,440	4,520	4,100
Asia	2,930	4,800	13,700	13,300
Australia/Oceania	22	33	714	692
Europe	667	682	2,770	2,790
North America	395	601	5,890	5,870
South America	267	454	11,700	10,400
World	4,830	8,010	39,300	37,100

Source: Adapted from Vörösmarty, C.J., et al., *Science*, 289, 284, 2000.

agricultural production to the amount of water consumed and (ii) economic WP is the magnitude of economic return per unit of water used. Therefore, the strategy is to enhance WP through the use of innovative options. Important among these innovative irrigation practices are regulated deficit irrigation, limited irrigation, and controlled alternative partial root zone drying (PRD) (Fang et al. 2010). These irrigation practices can save 15%–35% of water and increase WP by 10%–30% (Kang et al. 2002). Wastewater reuse is also an ecologically sustainable and hygienically safe approach (Neubert 2009; Chapter 11).

2.4 MANAGING GREEN WATER IN RAINFED AGRICULTURE

The grain yields in developing countries for rainfed (dryland) farming are about half of those from irrigated croplands (1.5 vs. 3.1 Mg/ha) (Rosegrant et al. 2009). The low productivity of rainfed agriculture is largely attributed to recurring drought stress during the growing season. The large yield gap between the actual and attainable yields (Table 2.6) can be narrowed by improving the use efficiency of green water or the precipitate stored in the soil. The adverse impacts of the extreme interannual variability in the rainfall, large uncertainty, and erratic distribution can be partly addressed by enhancing storage and improving the WP (2.8). The water requirements also depend on the crop type, growth duration, rooting depth, canopy cover, leaf characteristics, etc. Thus, there are large differences in

TABLE 2.5
Comparative Water Balances for Different Biomes

	Components of the Hydrologic Cycle (mm/year)				
Biome	**Precipitation (P)**	**Runoff (R)**	**Evapotranspiration (ET)**	**ET:P**	**R:P**
Arid	111	8	103	0.93	0.07
Semiarid	385	35	350	0.91	0.09
Semihumid	726	145	581	0.80	0.20
Humid	1142	426	716	0.63	0.37
Tropical	2580	1480	1100	0.43	0.57
Hyper humid	1093	688	405	0.37	0.63
Global	825	340	489	0.59	0.41

Source: Adapted from Shen, Y. and Chen, Y., *Hydrol. Process.,* 24, 129–135, 2010.

TABLE 2.6
Actual Yields of Rainfed Grain Crops as a Percentage of Attainable Yield

Country	% of Attainable Yield	Yield Improvement Factor by RMPs
Botswana	27.6	3.6
Burkina Faso	23.7	4.2
Ethiopia	31.6	3.2
India	42.1	2.4
Iran	18.4	5.4
Iraq	17.1	5.8
Jordan	18.4	5.4
Kenya	28.9	3.5
Morocco	25.0	4.0
Niger	26.3	3.4
Pakistan	10.5	9.5
Syria	18.4	5.4
Tanzania	23.7	4.2
Thailand	52.6	1.9
Uganda	23.7	4.2
Vietnam	63.1	1.6
Yemen	10.5	9.5
Zambia	31.6	3.2
Zimbabwe	31.6	3.2

Source: Recalculated from Rockström, J., et al., *Agr. Water Manage.*, 97, 543, 2010.

consumptive water use, depending on the land use, the crop type and its management, the soil quality and its management, and the evaporative demand of the atmosphere. Drought stress on rainfed croplands is likely to be exacerbated with the projected climate change, and the decline in productivity may not be compensated by the CO_2 fertilization effect (Lobell et al. 2008; The Royal Society 2009). Yet, there are several options for improving crop production in dry environments (Chaves and Davies 2010). Exploiting genetic variations and selecting drought-tolerant/avoiding germplasms are important strategies (Edmeades et al. 1999; Richards et al. 2010; Saint Pierre et al. 2010). The use of agronomic practices for conserving soil water (i.e., mulch farming, conservation tillage, nutrient management, and time of planting) is also strategically important, especially to realize the genetic potential of improved cultivars. The basic principles and practices of enhancing green water storage in rainfed agriculture are outlined in Figure 2.8.

2.5 MANAGING WATER IN IRRIGATED AGRICULTURE

Only 16% of the land that is equipped for irrigation yields 40% of the global production (Fereres and Connor 2004; Muralidharan and Knapp 2009). Globally, 7100 km^3/year are used for food production, of which 5500 km^3/year are used in rainfed agriculture and 1600 km^3/year are used in irrigated agriculture (de Fraiture et al. 2007). By 2050, the total water demand for agriculture is expected to increase to 8,500–11,000 km^3/year (Rockström et al. 2010), depending on the development and adoption of new water saving technology. The competing demand for water for industry and urban uses and the climate change are likely to reduce the availability of water for irrigation. Thus, enhancing WUE and WP by decreasing losses, especially of soil water, is more important now than

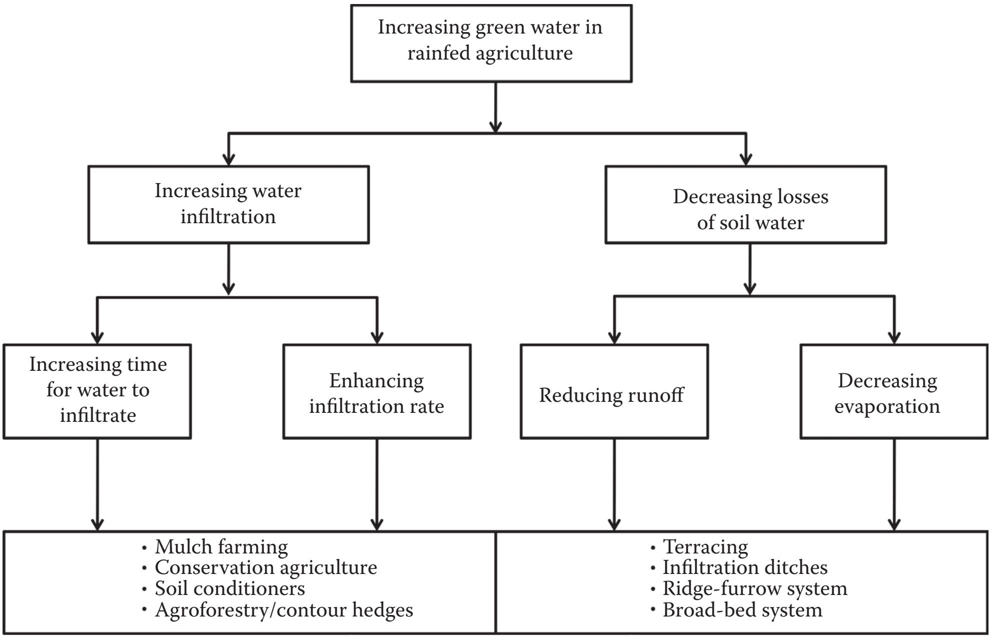
Increasing green water in rainfed agriculture
Increasing water infiltration
Decreasing losses of soil water
Increasing time for water to infiltrate
Enhancing infiltration rate
Reducing runoff
Decreasing evaporation
• Mulch farming
• Conservation agriculture
• Soil conditioners
• Agroforestry/contour hedges
• Terracing
• Infiltration ditches
• Ridge-furrow system
• Broad-bed system

FIGURE 2.8 Principles and practices of enhancing green water in rainfed agriculture.

ever before. The water footprint of irrigated crops must be reduced, so that the severe decline in the groundwater level in aquifers can be curtailed. The goal is to produce more crop per drop of water by managing the climate, water, soil, and crop. Rather than indiscriminate and excessive use of water, a holistic approach is needed to integrate the management of all natural resources. In addition, it is important for land managers to realize that irrigation water management is a dynamic process throughout the growing season (Muralidharan and Knapp 2009) and involves making critical choices with regard to the time to irrigate, the amount to irrigate, the method to irrigate, the fraction of soil area to irrigate, etc. Optimizing the use of irrigation water is essential to saving the dwindling water resources. The concept of PRD (Stoll et al. 2000) is proposed on the basis of root-to-shoot signaling (Dodd 2009). Repeated cycles of wetting and drying by PRD enhance the availability of plant nutrients. The use of root growth hormones and enhanced nodulation can also increase the agronomic yield in water-deficit environments (Diaz-Zorita and Fernández-Canigia 2009; Belimov et al. 2009). Water and plant nutrients (fertigation) must be delivered directly to the plant roots by drip subirrigation to minimize losses. Condensation irrigation, delivering water to the plant roots as vapors (as is the case in desert plants from the subsoil to the roots in the surface layer at night), is another option that must be explored. Strategies to enhance the WUE in irrigated agriculture are outlined in Figure 2.9.

2.6 ENHANCING WATER PRODUCTIVITY IN RAINFED AGRICULTURE

Rainfed agriculture accounts for 60% of the total agronomic production, but it has a low WP. Thus, improving WP can enhance global food production. There are several options for increasing the green water in rainfed agriculture. The basic principles are (i) increase water infiltration; (ii) store any runoff for recycling; (iii) decrease losses by evaporation and uptake by weeds; (iv) increase root penetration in the subsoil; (v) create a favorable balance of essential plant nutrients, especially of P; (vi) grow drought avoidance/adaptable species and varieties; (vii) adopt cropping/farming systems that produce a minimum assured agronomic yield in a bad season rather than those that produce the maximum yield in a good season; (viii) invest in soil/land restoration measures (i.e., terraces and

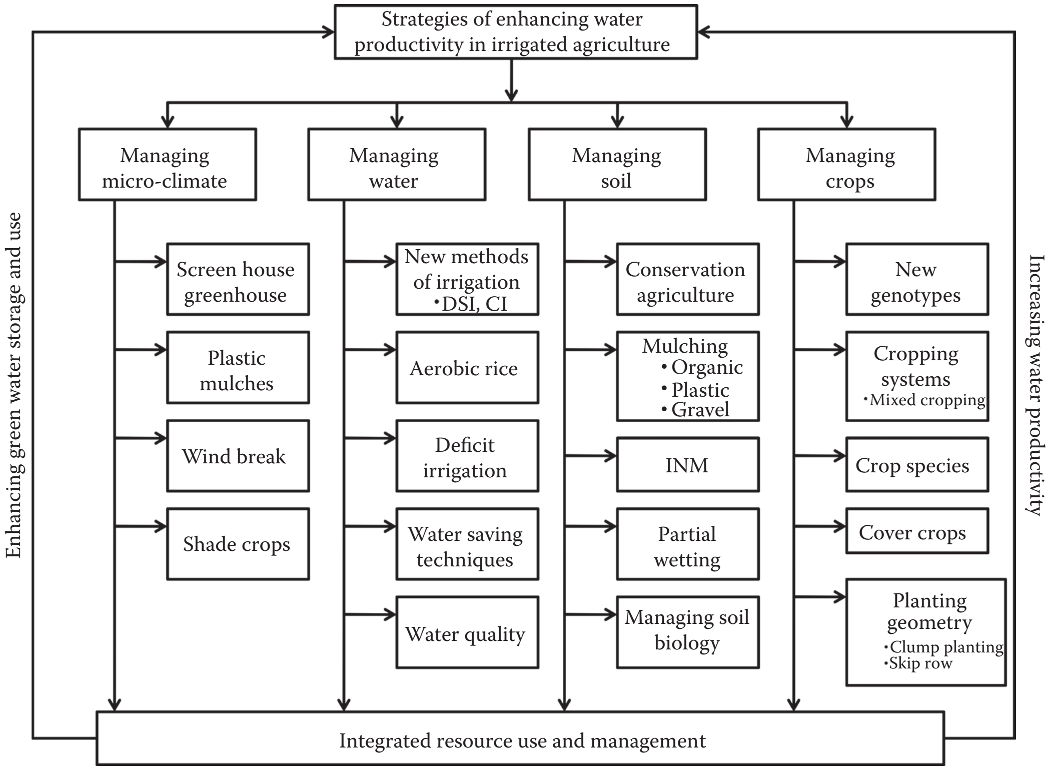
Strategies of enhancing water productivity in irrigated agriculture
Managing micro-climate
Managing water
Managing soil
Managing crops
Screen house greenhouse
Plastic mulches
Wind break
Shade crops
New methods of irrigation •DSI, CI
Aerobic rice
Deficit irrigation
Water saving techniques
Water quality
Conservation agriculture
Mulching •Organic •Plastic •Gravel
INM
Partial wetting
Managing soil biology
New genotypes
Cropping systems •Mixed cropping
Crop species
Cover crops
Planting geometry •Clump planting •Skip row
Integrated resource use and management
Enhancing green water storage and use
Increasing water productivity

FIGURE 2.9 Strategies of enhancing water-use efficiency in irrigated agriculture.

shelter belts); (ix) develop and use weather forecasting technology to facilitate the planning of farm operations; and (x) use precision or soil-specific farming technology using legume-based cropping systems to reduce losses of C and N (Drinkwater et al. 1998) and to improve soil fertility. Similarly, growing crops and varieties with better root systems is a useful strategy (Eissenstat et al. 2000) to reduce the risks in a harsh environment. The root system is important to drought resistance/tolerances (Passioura 1983). Based on these principles, the technological options for enhancing WUE in rainfed agriculture are listed in Figure 2.10.

2.7 RESTORING DEGRADED SOILS TO ENHANCE WATER PRODUCTIVITY

Alleviating soil-related constraints (i.e., nutrient deficiency, shallow rooting depth, and excessive soil erosion) is relevant to improving WP in both rainfed and irrigated agricultures. An adequate N availability, at the critical stage, is crucial to improving WP (Hatfield et al. 2001; Fang et al. 2010). In addition to N, the application of P can also improve WP (Liang 1996). A judicious use of fertilizer enhanced the WP in the irrigated cropland in the North China Plain from 0.23 to 0.90 kg/m^3 for cereal crops (Xu and Zhao 2001; Fang et al. 2010). The land application of organic wastes (Oldare et al. 2011) can improve the soil quality and increase the WP. The goal is to reduce water consumption without reducing the yields through agronomic management. This is achievable by (i) reducing water delivery losses, (ii) improving soil water availability to crop roots, and (iii) increasing the WP (Stanhill 1986). The agronomic practices that are effective in conserving soil water (green water), which also alter the soil surface energy balance, include mulch farming, plastic sheeting, and conservation tillage (Hatfield et al. 2001). The adoption of conservation-effective cropping systems, which reduce the soil erosion risks, is also relevant to improving the WP of soils prone to accelerated erosion. For highly erodible

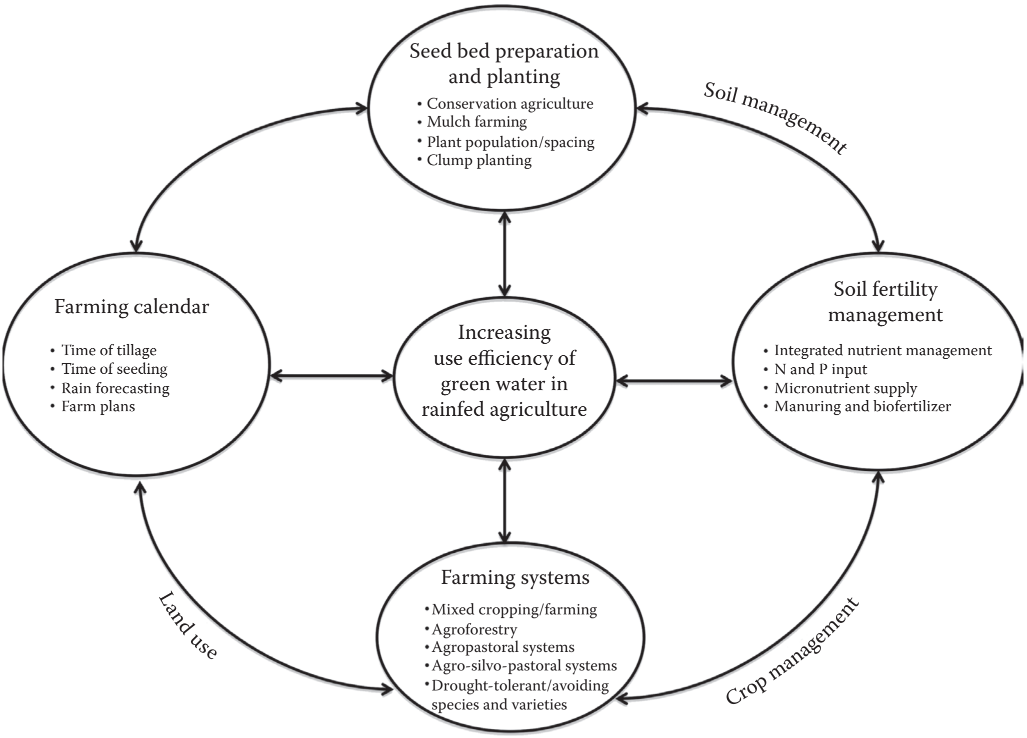
Seed bed preparation and planting
• Conservation agriculture
• Mulch farming
• Plant population/spacing
• Clump planting
Soil management
Farming calendar
• Time of tillage
• Time of seeding
• Rain forecasting
• Farm plans
Increasing use efficiency of green water in rainfed agriculture
Soil fertility management
• Integrated nutrient management
• N and P input
• Micronutrient supply
• Manuring and biofertilizer
Land use
Farming systems
• Mixed cropping/farming
• Agroforestry
• Agropastoral systems
• Agro-silvo-pastoral systems
• Drought-tolerant/avoiding species and varieties
Crop management

FIGURE 2.10 Some recommended management practices for improving water-use efficiency in rainfed agriculture.

soils of the semiarid Loess Plateau of China, Jun et al. (2010) observed that a forage–food–crop rotation is effective in reducing soil erosion and improving WP. The establishment of soil conservation practices in the semiarid Loess Plateau of China also improved the groundwater recharge (Gates et al. 2010).

The hydrological cycle, the C cycle, the nutrient cycle, and land management are intricately linked. Thus, a prudent approach is to enhance soil C sequestration by restoring the degraded soil and improving the WP (Bossio et al. 2008). Addressing soil degradation to improve WP is also a rational strategy. Meeting the food demands of the projected population of 9.2 billion by 2050 would require 30%–40% more water for agriculture with an optimistic scenario (de Fraiture et al. 2007), and 70%–90% more if the WP is not improved through soil restoration and the adoption of the recommended management practices (RMPs) (Bossio et al. 2008). With the realization that every land-use decision is also a water-use decision (Bossio et al. 2008), the adoption of sustainable agricultural techniques based on soil-specific RMPs can enhance WP. The data in Table 2.7, based on a survey of 144 projects, show that adopting RMPs improved WP by 16%–29% in irrigated agriculture and 70%–108% in rainfed agriculture (Pretty et al. 2006). Thus, adopting an RMP for agronomic improvement is essential to enhancing the WP.

2.8 BIOFUEL AND WATER DEMANDS

The conversion of biomass into modern biofuel is gaining momentum because of the climatic and environmental impacts of fossil fuel combustion and rising energy prices. Some examples of modern biofuels include bioethanol from corn grains and sugarcane (*Saccharum officinarum*) juice, and biodiesel from soybean and rape seeds (*Brassica napus*). The first-generation bioethanol is sugar-based or starch-based, the second generation is cellulose-based, the third generation is

TABLE 2.7
Increase in Water Productivity by Adoption of Sustainable Technologies Based on Recommended Management Practices in 144 Projects

Water Regime		Crops	Mean Water Productivity (kg/m³)		
			Without RMP	With RMP	Increase (%)
I	Rainfed				
		Cereals	0.47	0.80	70.2
		Legumes	0.43	0.87	102.3
		Roots and tubers	2.79	5.79	107.5
II	Irrigation				
		Rice	1.03	1.19	5.5
		Cotton	0.17	0.22	29.4

Source: Pretty, J., et al., *Environ. Sci. Technol.*, 40, 1114, 2006.

from the biomass of algae and cyanobacteria, and the fourth generation is hydrogen from the biomass. Consequently, there is a wide range of biofuel feedstock sources (Hattori and Morita 2010). Yet, the production of biofuel can put additional strain on water resources, especially in China and India (de Fraiture et al. 2008). Currently, biofuels account for about 100 km^3 of water use. However, relative water use is more for the production of feedstock on irrigated land, estimated at 44 km^3 out of a total of 2630 km^3. It takes approximately 2500 L of crop evapotranspiration and 820 L of irrigation water withdrawn to produce 1 L of biofuel (de Fraiture et al. 2008). Stone et al. (2010) estimated that the cubic meter of water that is required per milligram of ethanol is 580 for sugarcane, 2580 for corn grain, 1980 for switchgrass (*Panicum virgatum*), 9460 for grain sorghum (*Sorghum bicolor*), and 931 for sweet sorghum (Table 2.8). To meet the U.S. billion-ton vision, the current water requirement is 8.64×10^9 m^3, which will increase to 5.01×10^{10} m^3 by 2030 (Stone et al. 2010).

TABLE 2.8
Water Requirements for Biofuel

Crop		Crop Water Requirements for Biofuel	
		(m³ Water/Mg Fuel)	(m³ Water/GJ)
I	Ethanol		
	Corn (grain)	2380	97
	Sugarcane	580	22
	Corn (stover)	2465	92
	Corn (stover + grain)	1093	41
	Switchgrass	1980	74
	Grain sorghum	9460	354
	Sweet sorghum	931	35
II	Biodiesel		
	Soybean	9791	259
	Canola	4323	130

Source: Stone, K.C., et al., *Bioresour. Technol.*, 101, 2014, 2010.

2.9 AEROBIC RICE

Flooded rice is a water-intensive crop and has a low WP compared with upland rice. Rice requires two to three times more water to produce 1 kg of grains than other cereals. The intensive cultivation of flooded rice paddies in the rice–wheat (*T. aestivum*) system of the Indo-Gangetic Plains has depleted the groundwater reserves in northwest India (Rodell et al. 2009; Shan et al. 2006; Kerr 2009). Thus, there is a strong need to develop water-saving techniques for rice cultivation with a high WP. The goal is to produce similar yields but with a lower water consumption and a slight or no productivity loss. The strategy is to develop aerobic rice through genetic improvement (Farooq et al. 2009) and to identify agronomic practices involving rice cultivation without prolonged periods of inundation. There are improved systems of irrigation with considerable savings in water use (Kang and Zhang 2004). There are also physiological and ecological bases for water saving, including agronomic management involving seedbed preparation, the method of sowing, the date of sowing, nutrient management, weed control, and water management. The latter includes the irrigation method, the frequency of irrigation, and the amount of irrigation. Aerobic rice, growing rice in a method similar to other upland cereals (i.e., wheat), saves water and has a high WP (Bouwman et al. 2006, 2007; Bouwman and Tuong 2001). In an aerobic system, rice is grown in well-drained and unpuddled soil without flooding. A principal agronomic constraint in aerobic rice is weed control. Thus, the yield of aerobic rice can be 20%–30% lower than the total of flooded rice, but the WP is 1.6–1.9 times higher, resulting in a water saving of 35%–57% (Farooq et al. 2009). The WP of aerobic rice is more than that by alternative wetting and drying irrigation and mid-season drainage.

2.10 SOIL QUALITY AND WATER PRODUCTIVITY

Enhancing and sustaining soil quality are essential to improving WP. The soil organic matter (SOM) is an important parameter that affects the physical, chemical, biological, and ecological components of soil quality. Increasing the SOM concentration improves the soil's physical quality in terms of aggregation and aggregate strength, water infiltration rate, runoff and erosion, available water-holding capacity, and soil temperature; its chemical quality in terms of ion-exchange and cation-exchange capacities, nutrient storage and availability, nutrient use efficiency, and buffering against pH; its biological quality in terms of biodiversity, biological habitat and reservoir for the gene pool, gaseous exchange between the soil and the atmosphere, and C sequestration; and its ecological quality in terms of elemental cycling, ecosystem C budget, denaturing and filtering of pollutants, net primary and ecosystem productivity, etc. Increasing the SOM concentration implies creating a positive C (and N, P, S) budget(s) through adopting the following practices: conservation agriculture, mulching, cover cropping, manuring and biofertilizers, agroforestry, and other complex cropping/farming systems; the establishment of deep-rooted species/varieties, controlled grazing and improved pasture, precision farming, the use of biochar, etc. Principal challenges to increasing the SOM concentration are the lack of or the low rate of adoption of RMPs (listed above) and an abruptly changing climate. There are numerous uncertainties with regard to the response of the terrestrial (Friend 2010) and soil C pools (Norby et al. 2004; Heimann and Reichstein 2008) to changes in climate (i.e., temperature, precipitation, extreme events, soil moisture storage, and elemental cycling). Uncertainties are also attributed to the complexities created by the CO_2 fertilization effect, plant respiration and nutrient response (Leakey et al. 2009a,b), partitioning of biomass (Pendall et al. 2004), increased risks of soil erosion (Lal 2010), and alternation in decomposition because of any changes in the C:N ratio (Torbert et al. 2000; Norby et al. 2001).

2.11 DIETARY PREFERENCE AND WATER DEMAND

A meat-based diet has a large water and carbon footprint. The data in Table 2.9 show several orders of magnitude difference in the water requirement for plant-based and animal-based food. Food sources can be grouped on the basis of its water requirements into different categories, ranging from

TABLE 2.9
Liters of Water Needed to Produce 1 kg of Food

Water Requirement	Produce	Liters of Water (kg)	Relative Water Need
Low	Lettuce	125	1
	Tomatoes	183	1.5
	Cabbage	200	1.6
	Cucumber	233	1.9
	Potatoes	250	2.0
Medium	Oranges	459	3.7
	Apples	692	5.5
	Bananas	850	6.8
	Corn	892	7.1
High	Peaches/nectarines	1,183	9.5
	Wheat bread	1,284	10.3
	Wheat	1,350	10.8
	Mangos	1,584	12.7
	Avocados	1,834	14.7
	Tofu	1,867	14.9
	Groundnuts	3,068	24.5
	Rice	3,360	26.9
Very high	Chicken	3,900	31.2
	Olives	4,352	34.8
	Pork	4,800	38.4
	Cheese	6,000	48.0
Extremely high	Beef	16,000	128.0

Source: Modified and recalculated from Hoekstra, A.J. The water footprint of food. Twente Water Center, University of Twente, the Netherlands, 2011.

low to extremely high (Table 2.9). The preference for an animal-based diet, with a water requirement ranging from very high to extremely high, can exacerbate the already severe problem of water scarcity in many populous countries (i.e., China and India). Dietary choices must be discussed objectively at various levels of society and must be included in the school curricula.

2.12 STRATEGIES OF WATER MANAGEMENT

In arid and semiarid regions, already faced with the severe problems of water stress, the loss of blue water must be minimized by storing it for future use within the watershed. Because of the high evaporative demands both now and in the future, storage in aboveground impoundments is prone to high losses by evaporation. Thus, recharging the aquifers and creating belowground storage are preferred strategies. Gray water must be recycled and used for enhancing the production of the third generation of biofuels (i.e., algae and cyanobacteria) and for promoting urban agriculture, both of which are a high priority to meet the growing demands of an increasing and urbanizing human population.

2.13 CONCLUSION

A renewable freshwater supply is a finite resource. Similar to soil, water is also prone to misuse, contamination/pollution, and eutrophication. As much as 70% of total water withdrawal has been used for agriculture, mostly irrigation. However, there are numerous competing and essential uses (i.e., domestic, industrial, recreational, and aquaculture). While equipping some arable land in sub-Saharan Africa with irrigation facilities, the WP of existing irrigated land (i.e., China, India, Pakistan, Egypt, and Iran) must be improved, and new and innovative irrigation methods must be adopted. Because of its strong interaction, WP can be enhanced by improving the soil quality and increasing the efficient use of N and other nutrients. The choice of biofuel feedstock must be based on water (land and nutrient) requirements. School curricula must teach about water (and C or energy) footprints of plant-based vs. animal-based diets. The relative proportion of green water must be increased by improving water infiltration and enhancing soil water storage. Losses of blue water (surface runoff, interflow, river discharge) must be minimized by improving the aquifer recharge and enhancing the subsurface storage. Every drop must be recycled and used for multiple purposes. Win-win scenarios must be identified.

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Section II

Water Resources and Agriculture

3 Changes in Precipitation during the Twentieth Century across a Latitude Gradient in the United States

Anjali Dubey and Rattan Lal

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3.1 INTRODUCTION

An increase in the atmospheric concentration of greenhouse gases (GHGs) is causing global warming and abrupt climate change (IPCC 2007). The effects of climate change are multiple and vary across the planet. An important concern is the change in precipitation across the biomes. An increase in anthropogenic radiative forcing may increase the amount of atmospheric water vapor, which may destabilize the atmosphere and alter the precipitation regime (Kunkel 2003).

It is generally perceived that dry areas are reportedly getting drier and wet areas are getting wetter (Dore 2005). For example, Karl and Knight (1998) reported a 10% increase in the annual precipitation across the United States, while Groisman and Easterling (1994) reported only a 4% increase in the annual precipitation in the continental United States within the last century. During the early part of the twentieth century, however, precipitation either decreased or did not change significantly. Yet, it has increased significantly in the latter half of the twentieth century (Bradley et al. 1987; Diaz and Quayle 1980; Klugman 1983). The total increase in precipitation is attributed to the increase in its frequency and intensity (Karl and Knight 1998). A general trend of short-duration extreme precipitation indicates an increase in the frequency of events between 1931 and 1996, especially in the southwestern United States, across the southern Great Plains, and into the southern Great Lakes region and the Northeast (Kunkel et al. 1999). By contrast, a downward trend has been observed in the northwestern United States and Florida (Kunkel et al. 1999). These trends are in accord with the conclusions of the IPCC (1996) that the hydrological cycle is likely to become more intense in warmer climates, which may lead to an increase in heavy rain events.

Establishing long-term trends in precipitation across a large area can be difficult because of several inconsistencies in the instruments used over such a long period of time (Lettenmaier et al. 1994). Major factors that can affect precipitation include the mean latitude, longitude, elevation, distance from the coast, and slope aspect (Keim et al. 2005). The point precipitation measurements are also affected by the gauge undercatch bias, which is often larger in winter than in summer (Groisman and Legates 1994).

The changing climate has had a strong impact on increasing the magnitude of flood damage in the United States in the latter part of the twentieth century (Pielke and Downton 2000). Economic losses caused by floods in the United States are second only to those caused by hurricanes among all natural hazards, averaging \$3–\$4 billion annually (Changnon and Hewings 2001). An increase in the frequency of flooding in response to climate change is related to an alteration in the precipitation regimes in the United States (Karl and Knight 1998). The changing patterns of precipitation also affect the production of food crops, which is one of the major global concerns in the twenty-first century (Dore 2005). Excessive precipitation can damage crops, and the costs of crop losses and agricultural damage are expected to increase significantly with climate change (McCarthy 2001; Reilly et al. 2003; Rosenzweig et al. 2002). Between 1990 and 2010, floods in the Midwest, North Dakota, Red River, and Mississippi caused massive damage to crops, resulting in the loss of billions of dollars, and also delayed planting (Rosenzweig et al. 2002). An increase in precipitation also increases soil wetness and the risks of anaerobiosis, which makes plants more prone to diseases and insect infestation (Ashraf and Habib-ur-Rehman 1999). Farming operations, planting, and harvesting are also delayed because of the inability to operate machinery due to excessive rains and poor trafficability. Rosenzweig et al. (2002) observed that excessive soil moisture due to an increase in precipitation may double the maize production losses by 2030 in the United States. Loss in yields by the inundation of crops in the Midwest can also inflate food prices in the United States (Clemmitt 2008).

Nationally and internationally, water availability and water quality are relevant issues. Green water constitutes the rainwater that percolates into the soil, is held in retention pores, and is available for plant roots to absorb. By contrast, blue water is the water present in rivers, lakes, and aquifers (Rockström et al. 2009). By 2050, 59% of the global population will have a scarcity of blue water and 36% will have a shortage of both green and blue water (Rockström et al. 2009). Large biomes, which are responsible for the major ecosystem services, depend on approximately 90% of green water or terrestrial vapor flow to the atmosphere (Rockström and Gordon 2001). It is important to identify the technology that will provide efficient ways to manage green water resources, thereby lowering the risks of agricultural droughts and promoting global food security (Rockström et al. 2009).

It is in this context that the ecological and economic implications of changes in the hydrological cycle caused by climate change are extremely important and relevant. Thus, this chapter focuses on establishing any trends in precipitation across several states in the United States. The overall goal is to establish any fingerprints of climate change on the amount and distribution of annual and seasonal precipitation in diverse regions of the United States.

3.2 DATA AND METHODOLOGY

The total annual precipitation for stations in 11 states—Alaska, Minnesota, Ohio, Tennessee, Alabama, Hawaii, Oklahoma, Florida, Arizona, New Mexico, and Texas—was analyzed for 80–100 years. These sites were selected to represent diverse climates and ecoregions, such as boreal forests, tropical rainforests, temperate continental, humid subtropical, and semiarid climates. The selection of the stations was based on the accuracy of the data, the length of the period, the availability, and on the least missing data, since the historical climate records have been archived for these stations. The precipitation trends were analyzed both on an annual basis and for the growing season. In this chapter, the growing season is defined as the frost-free period (Table 3.1).

TABLE 3.1
Locations and Descriptions of Stations

Station	Latitude and Longitude	Height (Meters above Sea Level)	Data Coverage	MAP (cm)	Köppen Climate Classification
Waseca, MN	44°04′N, 93°32′W	351.4	1915–2010	78.97	Humid continental
Jackson, TN	35°37′N, 88°51′W	121.9	1903–2010	129.78	Humid subtropical
Fairhope, AL	30°33′N, 87°53′W	7.0	1920–2010	165.94	Humid subtropical
Moore Haven Lock, FL	26°50′N, 81°05′W	10.7	1922–2010	122.43	Tropical monsoon
Lihue, HI	21°59′N, 159°20′W	30.5	1950–2010	103.42	Tropical rainforest
University Experiment Station, AK	64°51′N, 147°52′W	144.8	1916–2010	30.61	Continental subarctic (boreal)
Coshocton, OH	40°22′N, 81°47′W	347.5	1956–2010	94.21	Hot summer continental
Wooster, OH	40°47′N, 81°55′W	310.9	1897–2010	93.62	Hot summer continental
Bellefontaine, OH	40°21′N, 83°46′W	361.2	1895–2010	92.06	Hot summer continental
Bowling Green, OH	41°23′N, 83°37′W	205.7	1894–2010	82.56	Hot summer continental
Circleville, OH	39°37′N, 82°57′W	205.1	1896–2010	99.32	Hot summer continental
Anahuac, TX	29°47′N, 94°38′W	7.3	1910–2010	133	Humid subtropical

(*continued*)

TABLE 3.1 (Continued)
Locations and Descriptions of Stations

Station	Latitude and Longitude	Height (Meters above Sea Level)	Data Coverage	MAP (cm)	Köppen Climate Classification
Whitney Dam, TX	31°52′N, 97°23′W	175	1950–2010	85.95	Humid subtropical
San Jon, NM	35°07′N, 103°20′W	1289.3	1910–2010	41.94	Semiarid
Caballo Dam, NM	32°54′N, 107°19′W	1277.1	1937–2010	24.25	Semiarid
Roosevelt, AZ	33°40′N, 111°09′W	672.1	1906–2010	140.77	Semiarid
Bartlett Dam, AZ	33°49′N, 111°39′W	502.9	1940–2010	34.79	Semiarid
Stillwater, OK	36°07′N, 97°06′W	272.8	1893–2010	85	Humid subtropical

Source: National Climatic Data Center.
Note: MAP: mean annual precipitation.

The sites selected for the study were located in 11 states across a north–south gradient in the United States: Waseca (Minnesota), Jackson (Tennessee), Fairhope (Alabama), Moore Haven Lock (Florida), Lihue (Hawaii), University Experiment Station (Alaska), Stillwater (Oklahoma), Roosevelt and Bartlett Dam (Arizona), San Jon and Caballo Dam (New Mexico), Anahuac and Whitney Dam (Texas), and five stations in Ohio: Coshocton, Wooster, Circleville, Bowling Green, and Bellefontaine (Figures 3.1 and 3.2). Data representing the precipitation measurements were collected from the National Climatic Data Center (www.ncdc.noaa.gov). These data were analyzed to establish trends in the annual and seasonal precipitation for all of the stations. Regression analysis was performed using Microsoft Excel (2007) and StatTools 5.7. A confidence interval of 90% was used while calculating the p values of the models. The growing season is the time between the last frost and the first frost of the year (Burkhead 1972). The period between May and October was used to categorize the growing season data for all states.

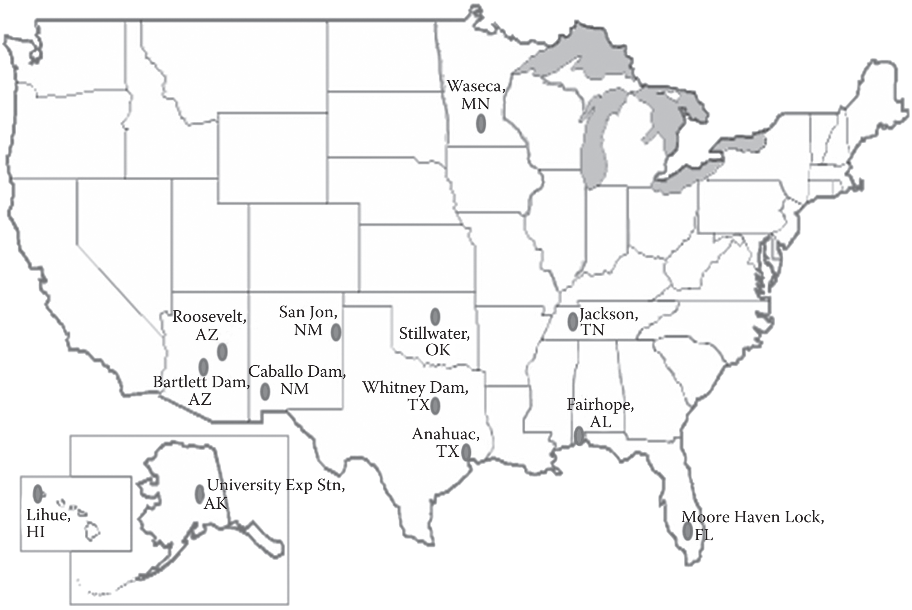

FIGURE 3.1 The locations of the stations used in the study.

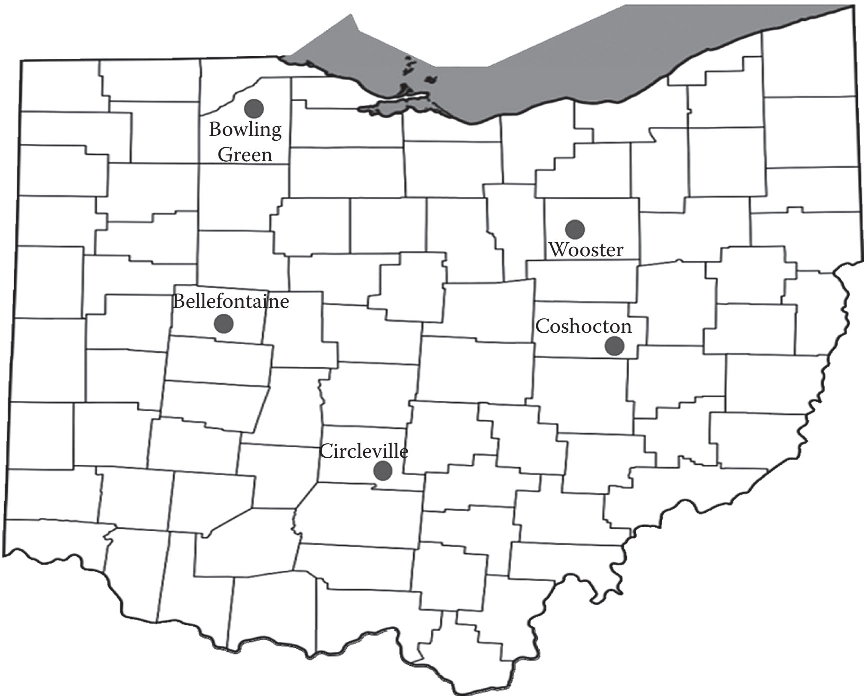

FIGURE 3.2 The locations of the stations in Ohio used in the study.

3.3 RESULTS

3.3.1 UNIVERSITY EXPERIMENT STATION, ALASKA

This site was selected for the study because Alaska is situated in the northwest extremity of the North American continent and represents an arctic biome. Thus, it is important to analyze and compare the data from this site with those in the continental United States. No major significant changes were observed on average in the amount of annual precipitation or that during the growing season. The annual precipitation showed a nonsignificant decreasing trend at the rate of 0.003 cm/year, while the seasonal precipitation increased at 0.01 cm/year (Figure 3.3). The p values of 0.9 and 0.6 of the annual and the growing season trends, respectively, are not statistically significant.

3.3.2 WASECA, MINNESOTA

The annual precipitation in Waseca has increased over the last 95 years at an average rate of 0.28 cm/year (Figure 3.4). The trend during the growing season is similar to that of the annual precipitation trend, but the rate of increase is smaller. Thus, precipitation during the growing season increased at an average rate of 0.12 cm/year (Figure 3.4), which is almost half the rate of increase on the annual basis. The p values for both the annual and the growing season trends are statistically significant (Figure 3.4).

3.3.3 OHIO

Several stations were selected within Ohio to establish any north–south gradients in precipitation.

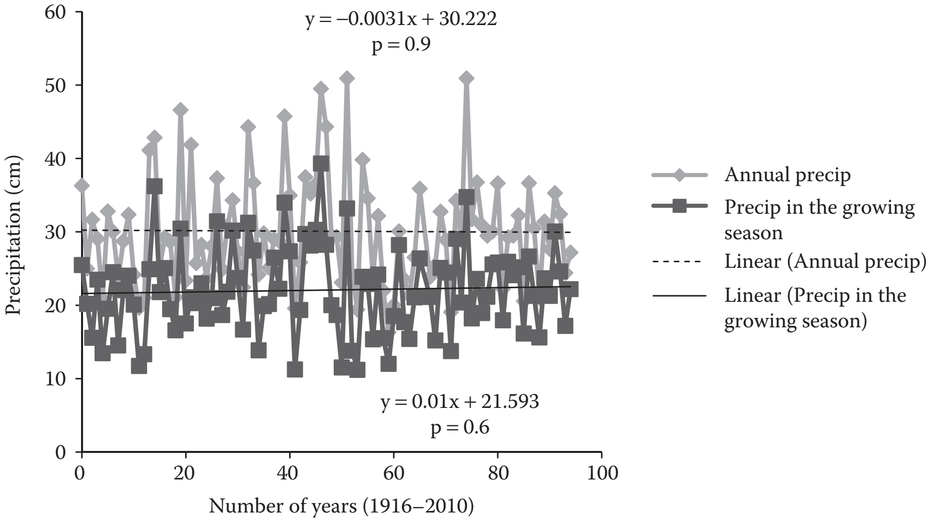

FIGURE 3.3 The trends in precipitation in University Experiment Station, AK, from 1916 to 2010.

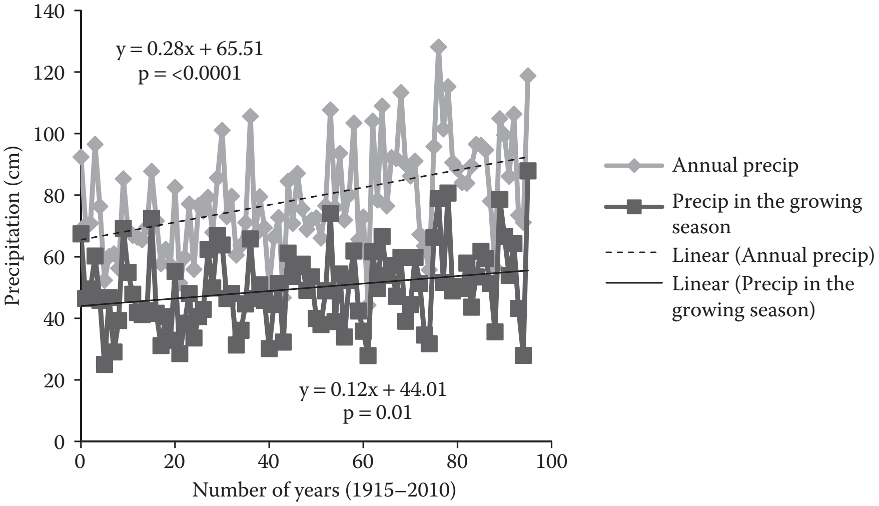

FIGURE 3.4 The trends in precipitation in Waseca, MN, from 1915 to 2010.

3.3.3.1 Coshocton

Coshocton is located in east central Ohio (Figure 3.5). Even though the National Climatic Data Center has data dating back to only 1956 for this site, there is a clear trend in the precipitation records. The annual precipitation increased at an approximate rate of 0.25 cm/year (Figure 3.5). The *p* value of 0.06 is statistically significant. The rate of increase in precipitation during the growing season is ~0.14 cm/year (Figure 3.5). However, the *p* value for this model is 0.2, which is not statistically significant.

3.3.3.2 Wooster

Wooster is located in northeastern Ohio (Figure 3.2) and the trend in precipitation is similar to that of Coshocton. The annual precipitation increased over the last 113 years (Figure 3.6). The rate of increase

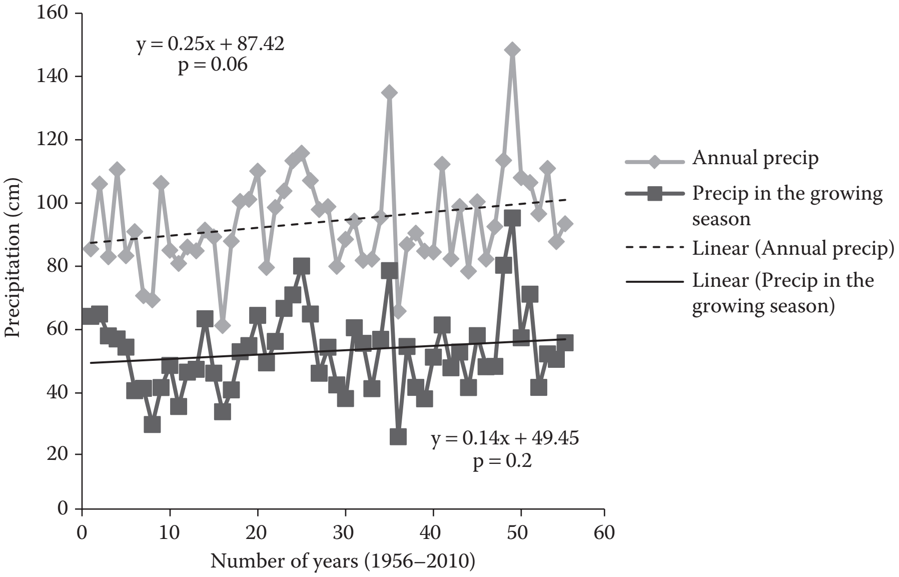

FIGURE 3.5 The trends in precipitation in Coshocton, OH, from 1956 to 2010.

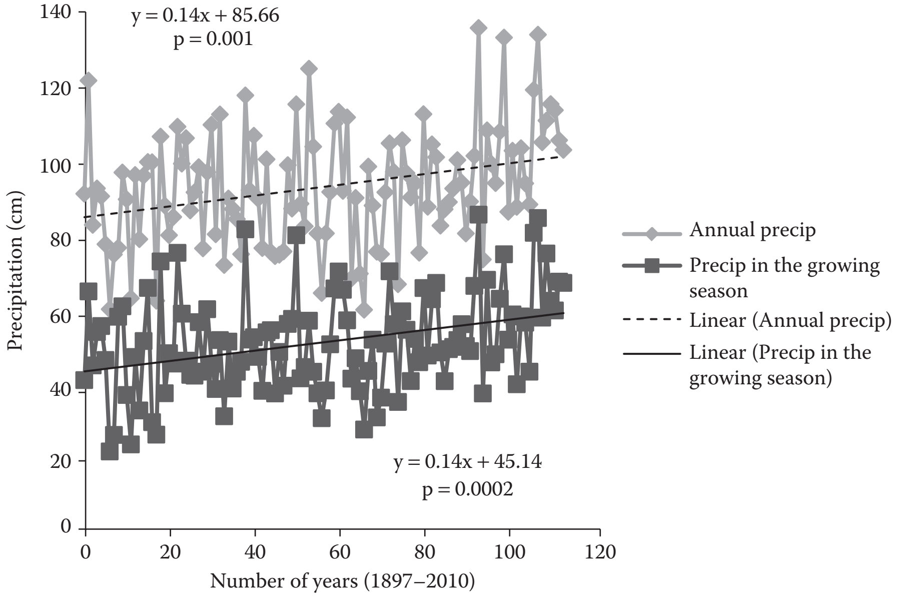

FIGURE 3.6 The trends in precipitation in Wooster, OH, from 1897 to 2010.

in the annual precipitation is ~0.14 cm/year, which is the same as the rate of increase during the growing season (Figure 3.6). The *p* values for both the trends were statistically significant (Figure 3.6).

3.3.3.3 Bellefontaine

Bellefontaine is located in west central Ohio (Figure 3.2). The precipitation records date back to 1895. An analysis of the data indicates some trends over the 115 years. The annual precipitation has increased at an average rate of ~0.1 cm/year (Figure 3.7), and it has a significant *p* value of 0.02. The precipitation during the growing season increased by ~0.05 cm/year (Figure 3.7), but the *p* value for the same is not

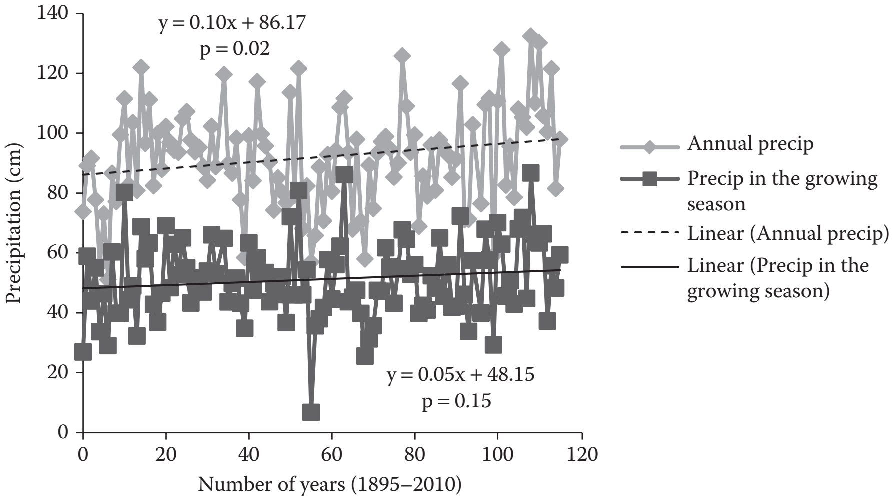

FIGURE 3.7 The trends in precipitation in Bellefontaine, OH, from 1895 to 2010.

statistically significant. These trends are not as prominent as for the sites in east central and northeastern Ohio.

3.3.3.4 Bowling Green

Bowling Green is located in northwest Ohio (Figure 3.2). Similar to the Bellefontaine site, only minor changes are observed in precipitation in Bowling Green between 1894 and 2010 (Figure 3.8). The rates of increase in precipitation are ~0.03 and ~0.04 cm/year annually and during the growing season, respectively. Both the trends have nonsignificant *p* values.

3.3.3.5 Circleville

Circleville is located in south central Ohio (Figure 3.2). For the period between 1896 and 2010, there are only minor changes in the precipitation patterns and the *p* values for the trends are nonsignificant.

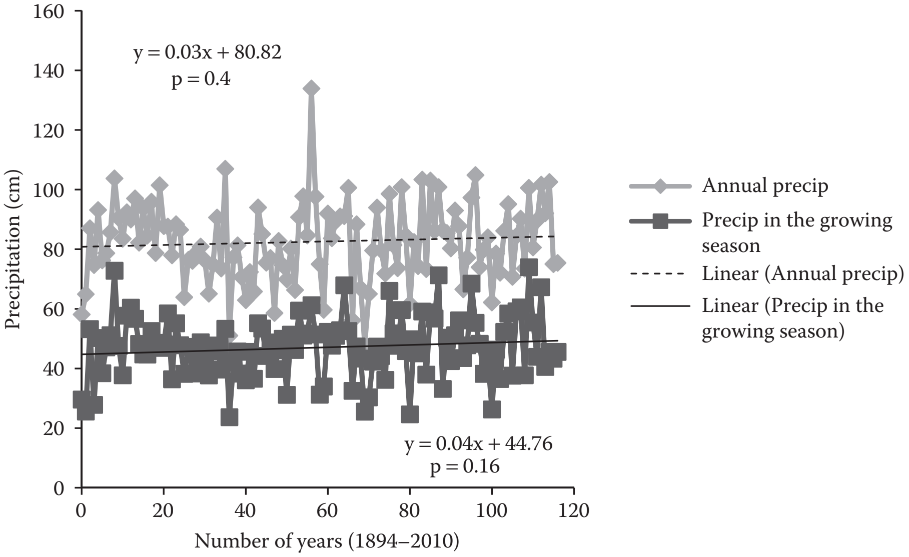

FIGURE 3.8 The trends in precipitation in Bowling Green, OH, from 1894 to 2010.

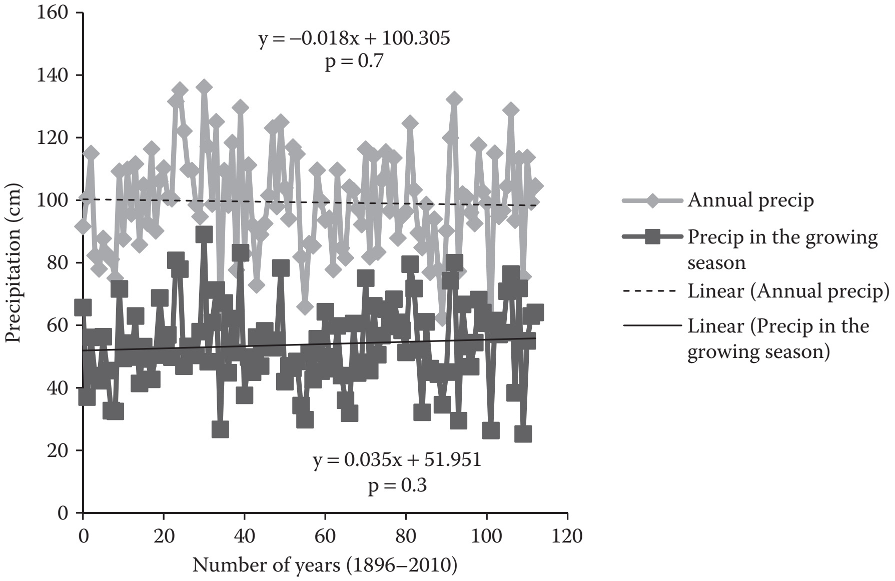

FIGURE 3.9 The trends in precipitation in Circleville, OH, from 1896 to 2010.

There has been a minor decrease in the annual precipitation at an average rate of ~0.018 cm/year (Figure 3.9). By contrast, precipitation has increased during the growing season at an average rate of 0.03 cm/year (Figure 3.9).

3.3.4 JACKSON, TENNESSEE

This station is located far south of Waseca, Minnesota (Figure 3.1), but the precipitation trend over the last century is rather similar. The annual precipitation has increased between 1903 and 2010, at an average rate of 0.2 cm/year (Figure 3.10), while the rate of increase during the growing season is ~0.14 cm/year (Figure 3.10). The *p* values for both the models are significant.

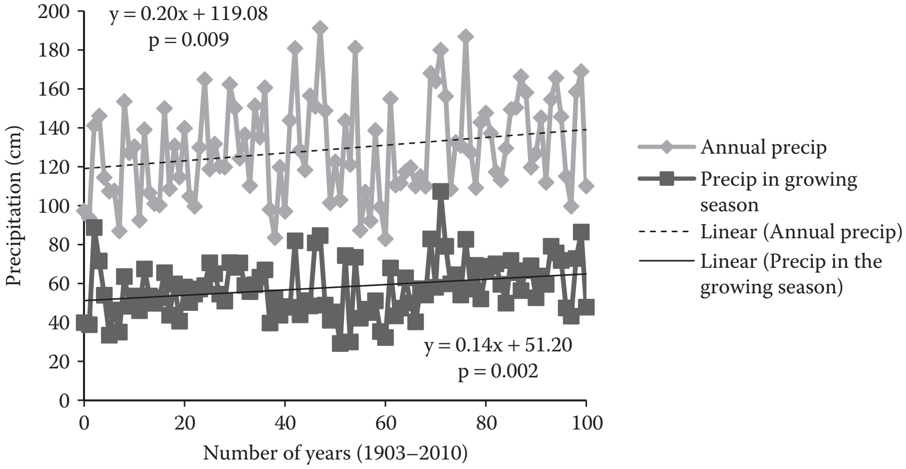

FIGURE 3.10 The trends in precipitation in Jackson, TN, from 1903 to 2010.

3.3.5 ARIZONA

The precipitation patterns were analyzed for two stations in central Arizona.

3.3.5.1 Bartlett Dam

Bartlett Dam is located in Maricopa County in central Arizona (Figure 3.1). There is no prominent trend in precipitation during the 61-year period between 1940 and 2010 and the *p* values are nonsignificant. The data in Figure 3.11a show a slight increase in the annual precipitation at a rate of ~0.12 cm/year. Precipitation during the growing season does not show any significant trend (Figure 3.11a). It is interesting to note that in the last two decades, however, precipitation has decreased significantly (*p* value = 0.03) at a rate of ~1 and 0.5 cm/year annually and during the growing season, respectively (Figure 3.11b).

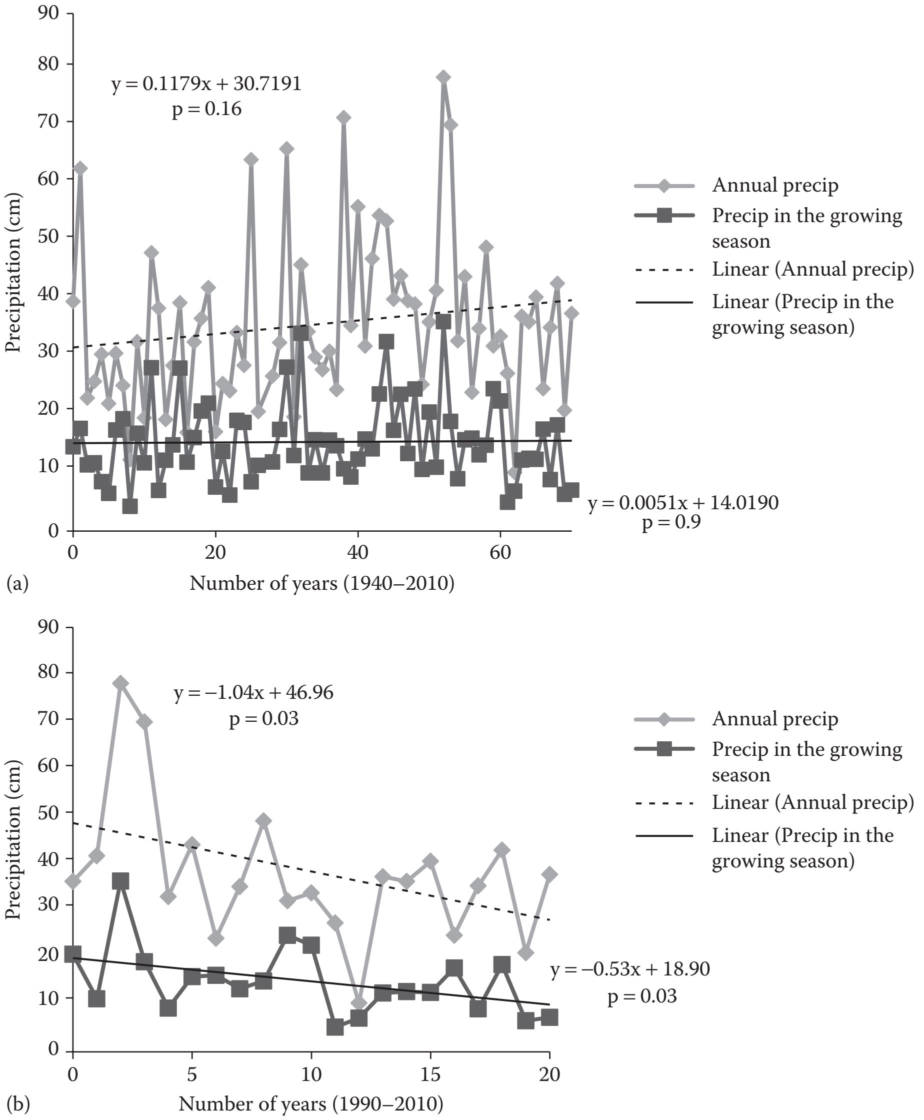

FIGURE 3.11 The trends in precipitation in Bartlett Dam, AZ: (a) from 1940 to 2010 and (b) from 1990 to 2010.

3.3.5.2 Roosevelt

Roosevelt is also located in central Arizona (Figure 3.1). The precipitation trends look similar to those in Bartlett Dam, Arizona, but are not statistically significant. The average precipitation has decreased annually as well as during the growing season within 105 years. Between 1906 and 2010, precipitation has decreased at an average rate of ~0.13 and 0.07 cm/year annually and during the growing season, respectively (Figure 3.12a). There has been a sharper decrease in the last two decades. The annual precipitation decreased significantly at a rate of ~1.54 cm/year, while the seasonal precipitation decreased at a rate of ~0.3 cm/year (Figure 3.12b).

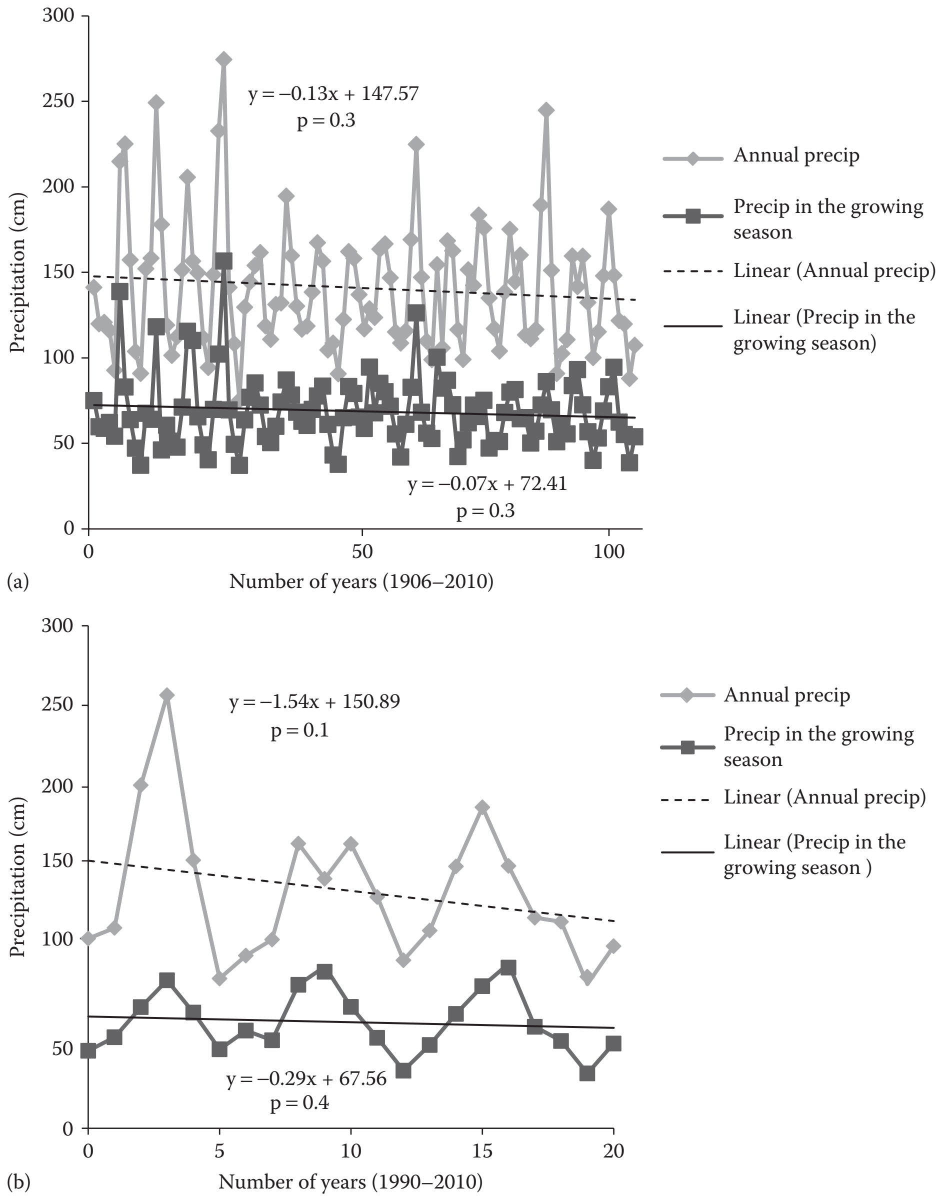

FIGURE 3.12 The trends in precipitation in Roosevelt, AZ: (a) from 1906 to 2010 and (b) from 1990 to 2010.

3.3.6 New Mexico

Two sites from different parts of New Mexico were studied.

3.3.6.1 San Jon

San Jon is located in northeastern New Mexico. The data in Figure 3.13a show that during the last 101 years, the annual precipitation has increased at ~0.05 cm/year. There is no clear trend in the growing season precipitation between 1910 and 2010 (Figure 3.13a). The *p* values for the 101-year period are not statistically significant. However, similar to Arizona, a very sharp decrease in the precipitation trend is observed in New Mexico since 1990. Precipitation has decreased at an

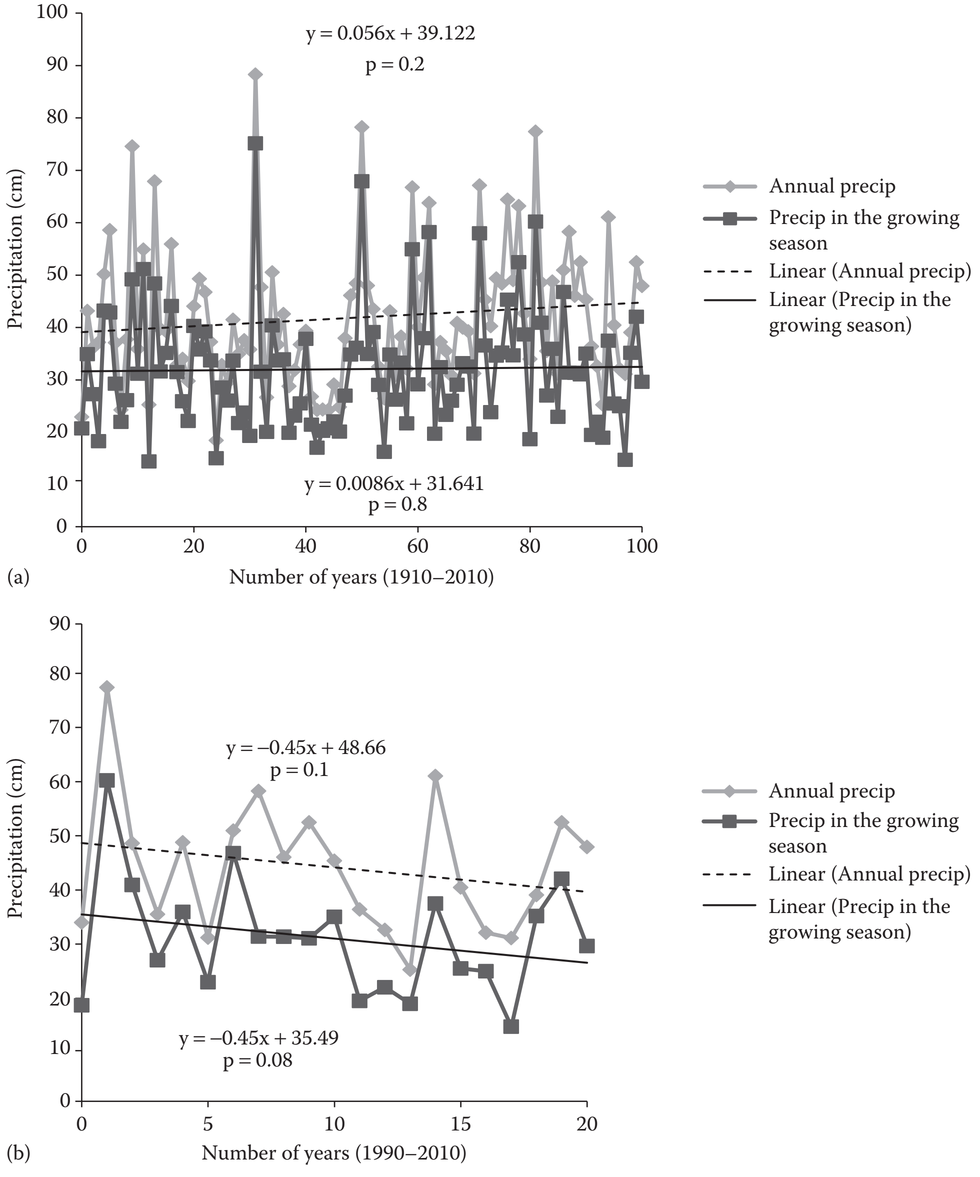

FIGURE 3.13 The trends in precipitation in San Jon, NM: (a) from 1910 to 2010 and (b) from 1990 to 2010.

average rate of ~0.45 cm/year between 1990 and 2010, both annually and during the growing season (Figure 3.13b) with significant *p* values.

3.3.6.2 Caballo Dam

Caballo Dam is located in southwestern New Mexico (Figure 3.1). The precipitation data were analyzed for a 71-year period between 1937 and 2010. An increasing trend was observed in the long-term data. The trend is statistically significant with the respective *p* values for the annual trend and the growing season trend—0.05 and 0.06. The rate of increase in the annual precipitation is ~0.12 cm/year (Figure 3.14a). However, the rate of increase in precipitation during the growing season is lower at ~0.8 cm/year (Figure 3.14a). Similar to the trends in other southern stations, the Caballo Dam site also shows a sharp decreasing trend in precipitation during the last two decades

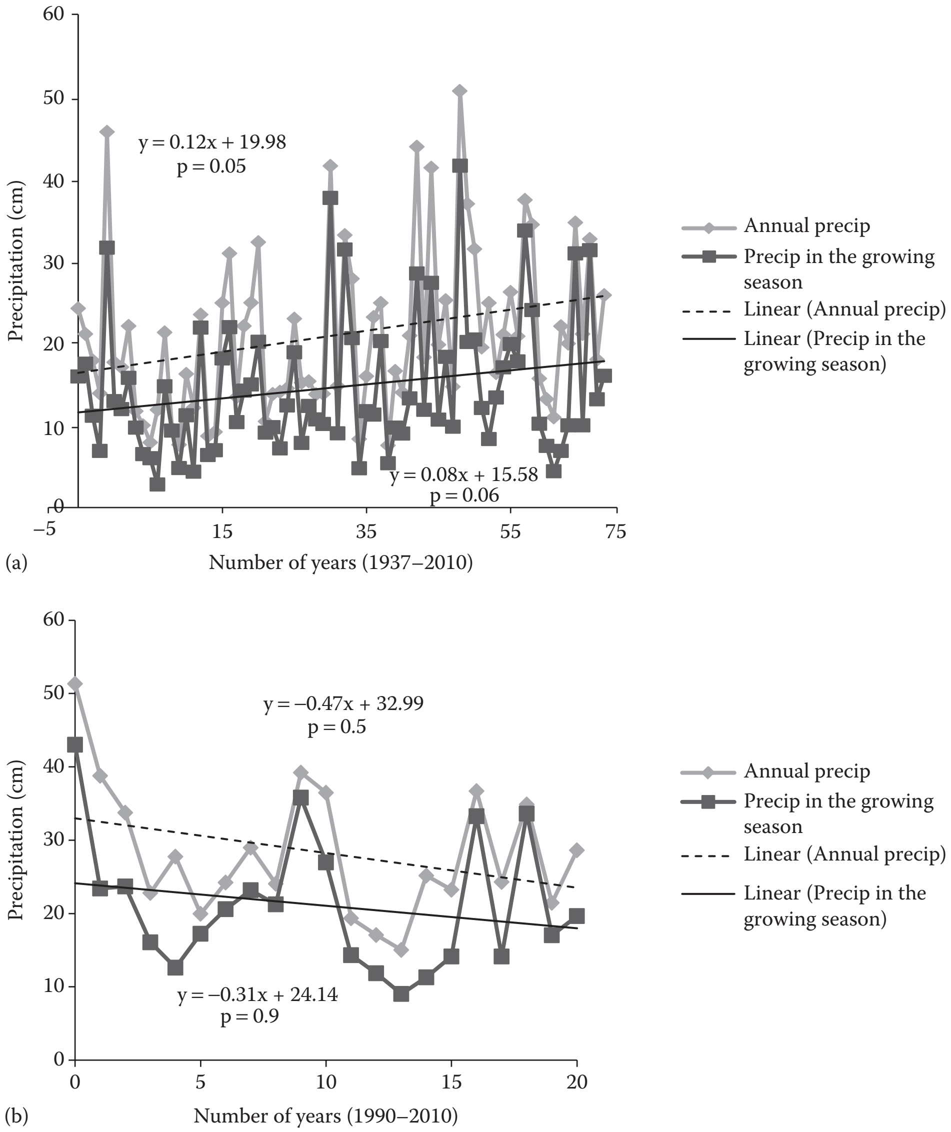

FIGURE 3.14 The trends in precipitation in Caballo Dam, NM: (a) from 1937 to 2010 and (b) from 1990 to 2010.

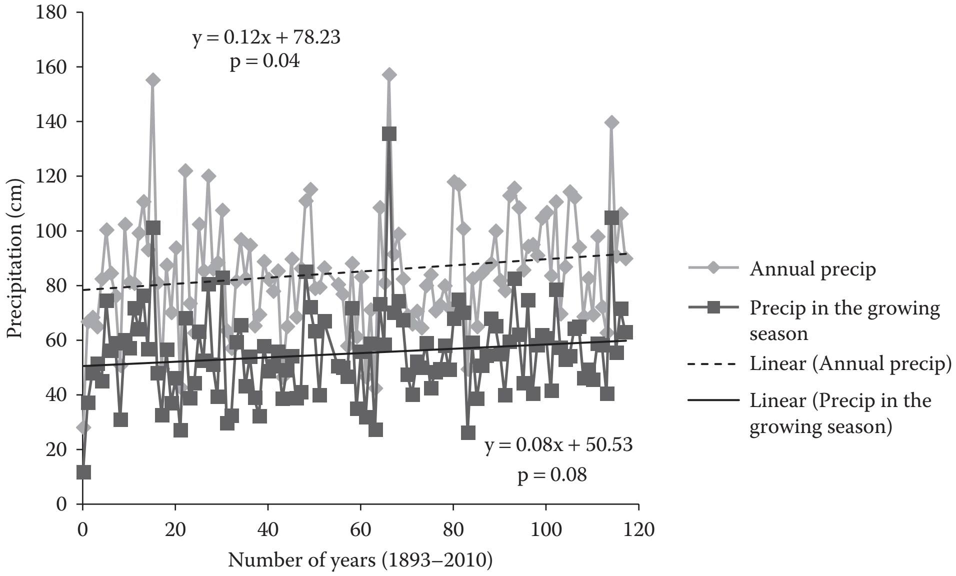

FIGURE 3.15 The trends in precipitation in Stillwater, OK, from 1893 to 2010.

(Figure 3.14b). The rate of decrease in precipitation between 1990 and 2010 is ~0.5 and 0.31 cm/year for the annual and seasonal precipitation, respectively (Figure 3.14b). However, the trends in the last 20 years are not statistically significant.

3.3.7 STILLWATER, OKLAHOMA

Stillwater is located in north central Oklahoma (Figure 3.1). The precipitation data were studied from 1893 to 2010. The annual precipitation has increased at a rate of ~0.1112 cm/year, with an especially high increase in the last two decades (Figure 3.15). Precipitation during the growing season has also increased at a rate of ~0.08 cm/year (Figure 3.15). Both the results are statistically significant.

3.3.8 TEXAS

Several parts of Texas experienced a severe drought during 2011. Thus, two stations were selected to analyze the long-term and short-term trends in precipitation.

3.3.8.1 Anahuac

Anahuac is located in eastern Texas. The precipitation records date back to 1910. A slight increasing trend in precipitation is observed over 101 years. Both the annual precipitation and that during the growing season have increased slightly at an average rate of ~0.1 cm/year between 1910 and 2010 (Figure 3.16a). However, during the last two decades, the annual precipitation has decreased at a rate of 0.95 cm/year, but the seasonal precipitation does not show any specific trend (Figure 3.16b). None of the results at this site is statistically significant.

3.3.8.2 Whitney Dam

This site is located in central Texas. The trends in precipitation are similar to the station in eastern Texas. There is a small increasing trend in precipitation within the last 61 years. The rate of increase

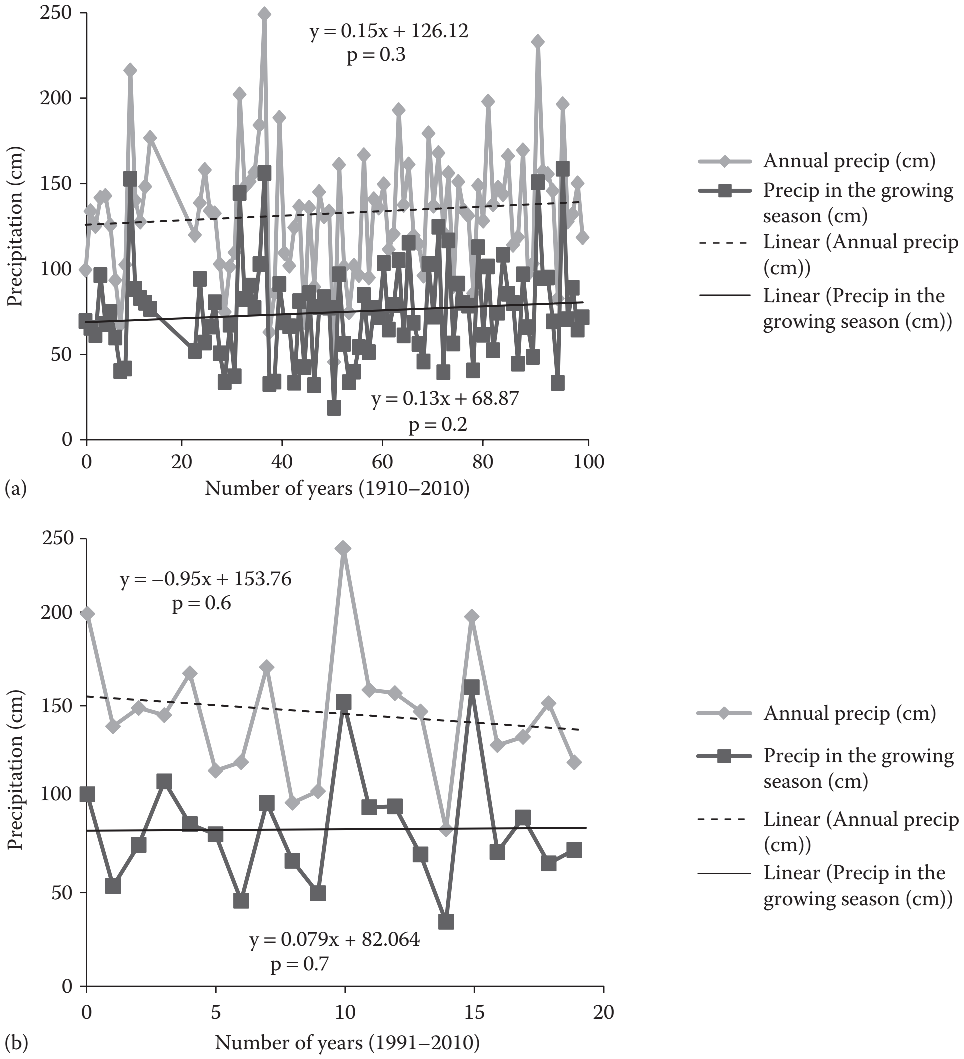

FIGURE 3.16 The trends in precipitation in Anahuac, TX: (a) from 1910 to 2010 and (b) from 1991 to 2010.

in the annual precipitation is ~0.18 cm/year (Figure 3.17). Precipitation during the growing season does not show any definite statistically significant trend (Figure 3.17).

3.3.9 Fairhope, Alabama

The data in Figure 3.18 show an overall increase in the annual precipitation in Fairhope, Alabama, even though the rate of increase is not as high as that in Waseca, Minnesota. Similarly, the rate of increase in precipitation during the growing season is much smaller than the rate of increase in the annual precipitation. Between 1920 and 2010, precipitation increased at a rate of ~0.2 cm/year (Figure 3.18). The increase is statistically significant. However, the rate of increase during the growing season is merely ~0.0809 cm/year and is nonsignificant (Figure 3.18).

3.3.10 Moore Haven Lock, Florida

Rather than an increasing trend, the annual precipitation in Moore Haven, Florida, and other southern sites in the United States indicates statistically significant declining trends. For example, the

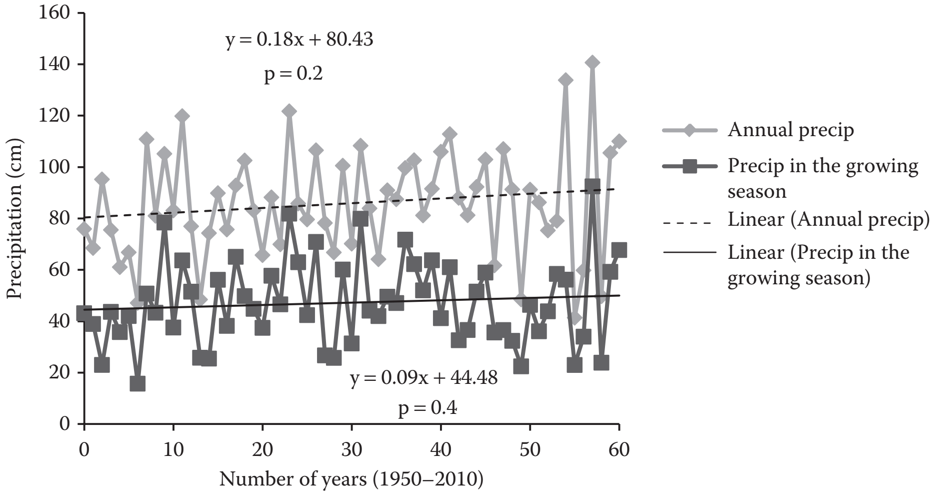

FIGURE 3.17 The trends in precipitation in Whitney Dam, TX, from 1950 to 2010.

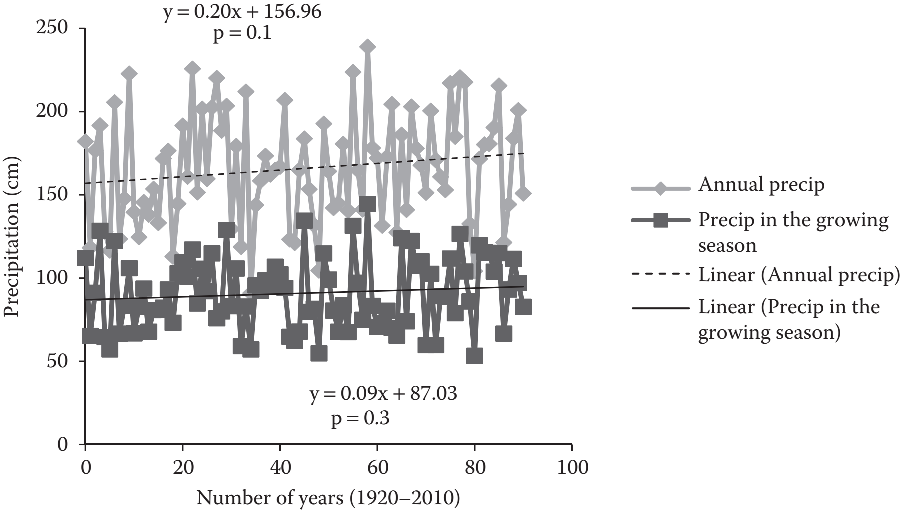

FIGURE 3.18 The trends in precipitation in Fairhope, AL, from 1920 to 2010.

annual precipitation has decreased at Moore Haven Lock in Florida over the 88-year period between 1922 and 2010. Between 1922 and 2010, the annual precipitation decreased at a rate of ~0.14 cm/year (Figure 3.19). Furthermore, the rate of decline is even more during the growing season, at an average rate of 0.2 cm/year (Figure 3.19).

3.3.11 LIHUE, HAWAII

Hawaii was included in this study because it is located southwest of the continental United States and represents the tropical rainforest biome. It has a warm tropical climate, which differs from all other sites included in this study. However, the data availability for Lihue, Hawaii, is limited to 60 years, from 1950 to 2010. Yet, there is a statistically significant declining trend in the annual precipitation during the last 60 years. The rate of decrease in the annual precipitation is approximately 0.4 cm/year

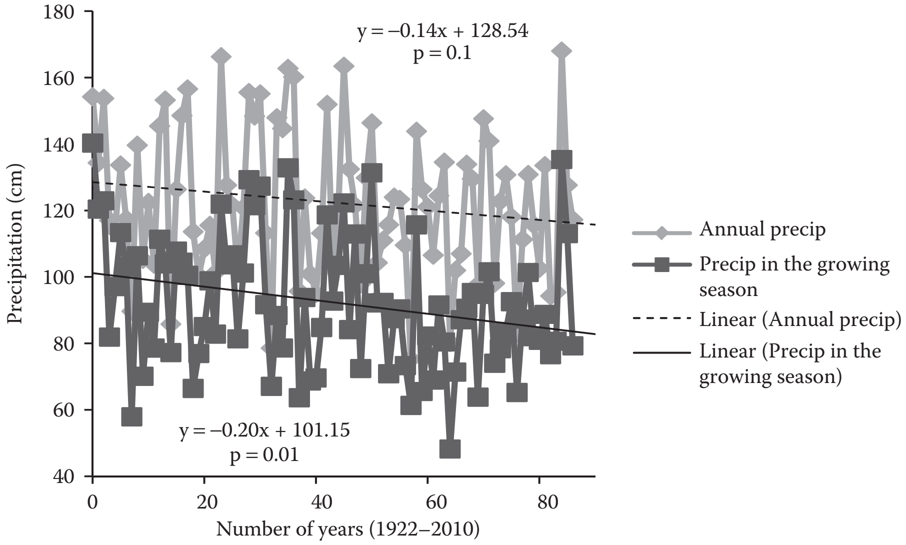

FIGURE 3.19 The trends in precipitation in Moore Haven Lock, FL, from 1922 to 2010.

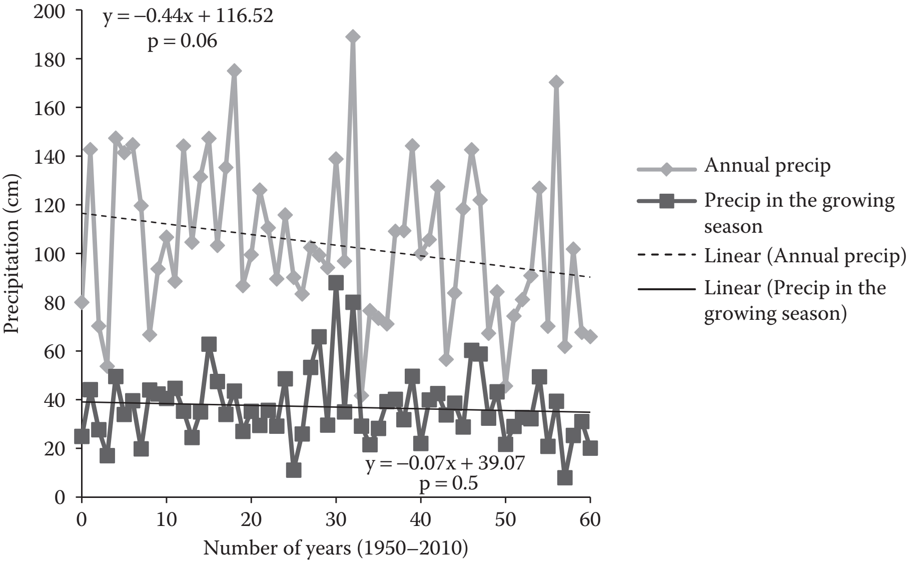

FIGURE 3.20 The trends in precipitation in Lihue, HI, from 1950 to 2010.

(Figure 3.20). However, the rate of decrease in precipitation during the growing season is relatively small and statistically nonsignificant at 0.07 cm/year (Figure 3.20).

3.4 DISCUSSION

This study shows no significant precipitation trend in the Alaskan site. However, an increasing trend is observed for sites located in Minnesota, Tennessee, Alabama, and Oklahoma. By contrast, a decreasing trend is observed for sites in Florida and Hawaii. In Ohio, three sites show an increasing trend while two sites do not show any specific trend. In Texas, New Mexico, and Arizona, an overall increasing trend is observed during the last century. However, in the past two decades, the precipitation has decreased, resulting in droughts.

Stafford et al. (2000) reported an increase in the total precipitation for three of the four seasons throughout most of Alaska in a 50-year period (1948–1998), while a slight decreasing trend was observed during the summer months. The present study is based on the 95-year precipitation records from the University Experiment Station located in Fairbanks. However, neither the annual nor the growing season precipitation shows any specific trends. There is a slight but nonsignificant decrease in the annual precipitation and a nonsignificant increase in the seasonal precipitation.

In contrast to the data of the present study for Minnesota, Baker (1962) reported a declining trend in both the seasonal and the annual precipitation between 1900 and 1958 in Minnesota for five stations studied across the state. Yet, in the current study, the Waseca site located in southern Minnesota indicates an increasing trend in the long-term precipitation between 1915 and 2010 for both the annual precipitation and the growing season precipitation.

In the present study, the sites in east central and northeastern Ohio indicate an increasing trend in precipitation, while the increase is not significant in the sites located in northwestern, south central, and west central Ohio (Bellefontaine, Circleville, and Bowling Green). Harstine (1991) studied the precipitation trends in Ohio between 1931 and 1980 and found precipitation to be highest in southern and eastern Ohio and decreasing in northwestern Ohio.

The present study indicates a declining trend in the precipitation in Florida and in the Caribbean region. The precipitation data from land-based sites indicate a similar declining trend in some regions (Coleman 1982; Kunkel et al. 1999; Neelin et al. 2006). The data from Moore Haven Lock located in southern Florida also indicate a declining trend. The annual precipitation decreased between 1922 and 2010, and the rate of decrease in precipitation during the growing season is even higher.

In the Hawaiian Islands, the records from stations along the windward coastal side of the islands have shown a general decreasing trend in precipitation. By contrast, an increasing trend is reported along the southeast and northwestern sides of the Hawaiian Islands (Doty 1982; Woodcock and Jones 1970). The precipitation data from 1951 to 2000 have been analyzed from more than 100 stations across four major islands in Hawaii. A declining trend in precipitation has been reported since 1980 (Diaz et al. 2005). In the present study, data from Lihue also show a similarly decreasing trend in rainfall from 1950 to 2010. However, the rate of decrease is less pronounced for the growing season precipitation than for the annual precipitation.

For east central Texas, Harmel et al. (2003) reported that precipitation increased over a 61-year period between 1939 and 1999. It was also reported that precipitation in most sites in southern and central Texas increased historically between 1895 and 2006 (Nielsen-Gammon 2011). In the present study, both the Anahuac and Whitney Dam sites located in eastern and western Texas, respectively, also indicate an increasing trend. However, during the last 20 years, precipitation has a definite decreasing trend.

An increasing trend in precipitation has been reported in most of the Great Plains areas, including the stations located in south central, southwestern, northern, and eastern Oklahoma between 1981 and 2001 (Garbrecht et al. 2004). The data in the present study from Stillwater, located in north central Oklahoma, are in agreement with the hypothesis by Garbrecht et al. and also indicate an increasing trend in precipitation during the twentieth century.

It has been reported that dry areas in the United States are getting drier and wet areas are getting wetter (Dore 2005). The data analysis in the present study indicates that sites in the northern and midwestern states (Minnesota and Ohio) show an increasing trend in precipitation. The rate of increase is larger in the northern (Minnesota and Ohio) than in the southern states of Tennessee and Alabama. The trend in the annual precipitation is negative for some sites in the southwestern and southeastern United States—Hawaii, Arizona, and Florida. However, the annual precipitation is seemingly increasing in the south central United States—Texas and Oklahoma. Precipitation in Alaska, located in the extreme northwestern United States, does not show any definite trend. In New Mexico and Arizona, the precipitation in the last two decades has been decreasing.

Several states in the southern United States have experienced severe drought during 2011 (CNN 2011). The rainfall received during 2011 has been extremely low in Texas, Florida, New Mexico, and Oklahoma. The present study shows a sharp decreasing trend in precipitation during the last two decades in Florida and New Mexico, corroborating the drought experienced in 2011. However, no decreasing trend is observed for the sites located in Texas and Oklahoma. These observations are in agreement with the published literature (Garbrecht et al. 2004; Harmel et al. 2003; Nielsen-Gammon 2011). Several other factors may be responsible for severe droughts, such as an increase in temperature, evaporation, and the changing pattern of the oceanic currents (Fawcett et al. 2011; Seager et al. 2009). The rising demand for water resources due to the increasing population is another factor responsible for the deficit (Manuel 2008). The results and findings of the present study can be used to develop guidelines for adapting agricultural, industrial, ecological, and residential water management strategies in order to make the most efficient use of natural precipitation, since surface water and groundwater (blue water) supplies are also dependent on it. With the increasing population and further increasing water demand in the midst of climate change, sustainable water resource management can play a crucial role in agricultural and industrial economies.

3.5 CONCLUSION

The data presented support the following conclusions:

1. Precipitation trends are increasing in some regions across the United States, such as Minnesota, Tennessee, Ohio, Oklahoma, and Alabama, while decreasing in other regions, such as Florida and Hawaii, based on their geographic location, climate, and other factors (Table 3.2).
2. In New Mexico, Arizona, and Texas, there is an increasing trend in the long-term precipitation. However, in the last 20 years, precipitation has been decreasing.

TABLE 3.2
Summary of *p* Values and Significance for Different Stations

Station	Trend	*p* Values	Significant
Waseca, MN (1915–2010)	Annual	<0.0001	✓
	Growing season	0.01	✓
Jackson, TN (1903–2010)	Annual	0.009	✓
	Growing season	0.002	✓
Fairhope, AL (1920–2010)	Annual	0.1	✓
	Growing season	0.3	×
Moore Haven Lock, FL (1922–2010)	Annual	0.1	✓
	Growing season	0.01	✓
Lihue, HI (1950–2010)	Annual	0.06	✓
	Growing season	0.5	×
University Exp Stn, AK (1916–2010)	Annual	0.9	×
	Growing season	0.6	×
Coshocton, OH (1956–2010)	Annual	0.06	✓
	Growing season	0.2	×
Wooster, OH (1897–2010)	Annual	0.001	✓
	Growing season	0.0002	✓
Bellefontaine, OH (1895–2010)	Annual	0.02	✓
	Growing season	0.15	×

(*continued*)

TABLE 3.2 (Continued)
Summary of *p* Values and Significance for Different Stations

Station	Trend	*p* Values	Significant
Bowling Green, OH (1894–2010)	Annual	0.4	×
	Growing season	0.16	×
Circleville, OH (1896–2010)	Annual	0.7	×
	Growing season	0.3	×
Anahuac, TX (1910–2010)	Annual	0.3	×
	Growing season	0.2	×
Whitney Dam, TX (1950–2010)	Annual	0.2	×
	Growing season	0.4	×
San Jon, NM (1910–2010)	Annual	0.2	×
	Growing season	0.8	×
San Jon, NM (1990–2010)	Annual	0.1	✓
	Growing season	0.08	✓
Caballo Dam, NM (1937–2010)	Annual	0.05	✓
	Growing season	0.06	✓
Roosevelt, AZ (1906–2010)	Annual	0.3	×
	Growing season	0.3	×
Roosevelt, AZ (1990–2010)	Annual	0.1	✓
	Growing season	0.4	×
Bartlett Dam, AZ (1940–2010)	Annual	0.16	×
	Growing season	0.9	×
Bartlett Dam, AZ (1990–2010)	Annual	0.03	✓
	Growing season	0.03	✓
Stillwater, OK (1893–2010)	Annual	0.04	✓
	Growing season	0.08	✓

3. In Ohio, the data from the northeastern and the east central regions indicate a larger increase in precipitation over the twentieth century as compared with the western and the central parts.
4. In some cases, the increase in precipitation is more pronounced on an annual basis rather than during the growing season. In others, the trends are almost the same. Therefore, there can be a possible scenario where even though the total precipitation is increasing annually, the rate of increase during the growing season is rather small. A change in precipitation during the growing season is important for agricultural production.

ACKNOWLEDGMENT

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4 Desired Future Conditions for Groundwater Availability in the High Plains Aquifer System

Z. Sheng, C. Wang, J. Gastelum, S. Zhao, and J. Bordovsky

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4.1 INTRODUCTION

The High Plains Aquifer, also known as the Ogallala Aquifer, has been used extensively for agricultural production in the Great Plains. It covers part of eight states, extending from west Texas to South Dakota (USGS 2011a). The High Plains Aquifer provides water for agricultural production and urban uses. In 2000, a total of 24.2 billion cubic meters of groundwater (or at a rate of 66.2 million cubic meters per day, m^3/day) was pumped from the High Plains Aquifer (Maupin and Barber 2005), accounting for 30% of all groundwater used for irrigation in the United States (Guru and Horne 2000). Almost 97% of the pumped groundwater was used for irrigation; the remaining 3% was used for public, industrial, domestic, and other uses (Maupin and Barber 2005). In 2002, there were a total of 6.1 million ha of irrigated land in the High Plains area (USDA Census of Agriculture 2002; USGS 2011b), accounting for approximately one-fifth of all cropland in the United States. Alfalfa, corn, cotton, sorghum, soybeans, peanuts, and wheat are major crops in the High Plains region. These crops provide Midwest cattle operations with enormous amounts of feed and account for 40% of the feedlot beef output here in the United States (Guru and Horne 2000). The use of groundwater from the High Plains Aquifer has transformed this area into an important agricultural region that sustains more than one-fourth of the nation's agricultural production. Therefore, the current availability and future sustainable supply of high-quality groundwater are central to the overall health of the High Plains agricultural economy, the growth of its cities and rural communities, and the well-being of the ecosystem.

Historically, groundwater pumping since predevelopment (about the 1950s) has resulted in the depletion of groundwater in most of the aquifer area because pumping far exceeded its capacity to recharge and to capture the discharge. In addition, pumping has also caused depletion of surface water where the river is hydraulically connected with the shallow aquifer. Moreover, groundwater has also been contaminated due to long-term agricultural applications and other sources.

To secure water supplies for future agricultural production and community development, best management practice (BMP) strategies, including the adoption of high-efficiency irrigation technology, the Conservation Reserve Program of Natural Resources Conservation Service, and other programs have been implemented to slow down the depletion of groundwater storage and prevent contamination. Many projects have been conducted and are under way to gain a better understanding of the hydrological processes and develop better BMP strategies to extend the life of the aquifer and to sustain the economic development in the region. One of the recent attempts in preserving aquifer storage for future generations is to manage the utilization of the groundwater resources with the desired future conditions (DFCs). This chapter summarizes the current status of aquifers, impacts of historic pumping, and DFCs. Current DFCs aim at slowing down the depletion of aquifer storage, primarily based on water quantity and not water quality. In this chapter, we also examine factors that have influenced historic/current groundwater pumping practices and will have impacts on future groundwater availability and recommend a holistic analysis tool to link a hydrological model with an econometric model for the assessment of water users' behavior in response to groundwater depletion and socioeconomic factors.

4.2 PHYSICAL AND CULTURAL CHARACTERISTICS OF THE HIGH PLAINS AQUIFER

The High Plains Aquifer, the largest fresh aquifer system in the United States, covers 450,000 km^2 in parts of eight states—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Figure 4.1; USGS 2011a). The aquifer is further divided into three regional subdivisions—Northern High Plains (NHP), Central High Plains (CHP), and Southern High Plains (SHP); there is little groundwater flow in the aquifer between the regional subdivisions (Figure 4.1; Weeks et al. 1988). The High Plains Aquifer extends from south of 32° to almost 44° north latitude and from east of 96°30′ to almost 106° west longitude. The land surface elevation of the High Plains area

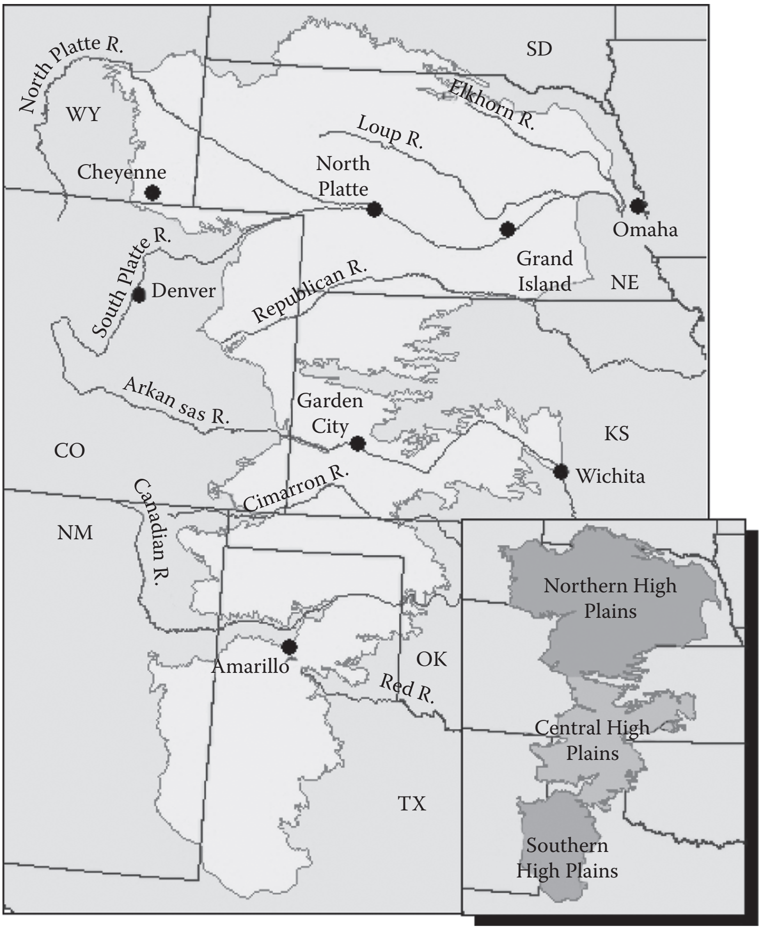

North Platte R.
WY
Cheyenne
SD
Elkhorn R.
Loup R.
North Platte
Omaha
Grand Island
NE
South Platte R.
Denver
Republican R.
Arkan sas R.
Garden City
KS
CO
Wichita
Canadian R.
Cimarron R.
NM
Amarillo
OK
Red R.
TX
Northern High Plains
Central High Plains
Southern High Plains

FIGURE 4.1 The High Plains Aquifer boundary and its subdivisions. (From USGS, High Plains Regional Ground Water Study, 2011, http://co.water.usgs.gov/nawqa/hpgw/images/figure1.jpg. Accessed September 30, 2011.)

ranges from about 2377 m above the National Geodetic Vertical Datum of 1929 (NGVD 29) on the western boundary to 354 m above NGVD 29 on the eastern boundary (USGS 2011a).

4.2.1 CLIMATE

The High Plains area is characterized by a middle-latitude dry continental climate with abundant sunshine, moderate precipitation, frequent winds, low humidity, and a high rate of evaporation. Mean annual temperature ranges from about 6.1°C in the north to 17.2°C in the south. Mean annual precipitation in the region varies from 305 mm in the west to 838 mm in the east (Figure 4.2). Pan evaporation ranges from about 1524 mm/year in northern Colorado to about 2667 mm/year in southeastern New Mexico. During most years, in much of the area, irrigation is required for economic yields of typical crops—alfalfa, corn, cotton, sorghum, soybeans, peanuts, and wheat (USGS 2011b).

4.2.2 HYDROGEOLOGICAL UNITS

The High Plains Aquifer consists of all or parts of several geologic units of the Quaternary and Tertiary age, as shown in Table 4.1 (Weeks and Gutentag 1984). The Brule Formation of

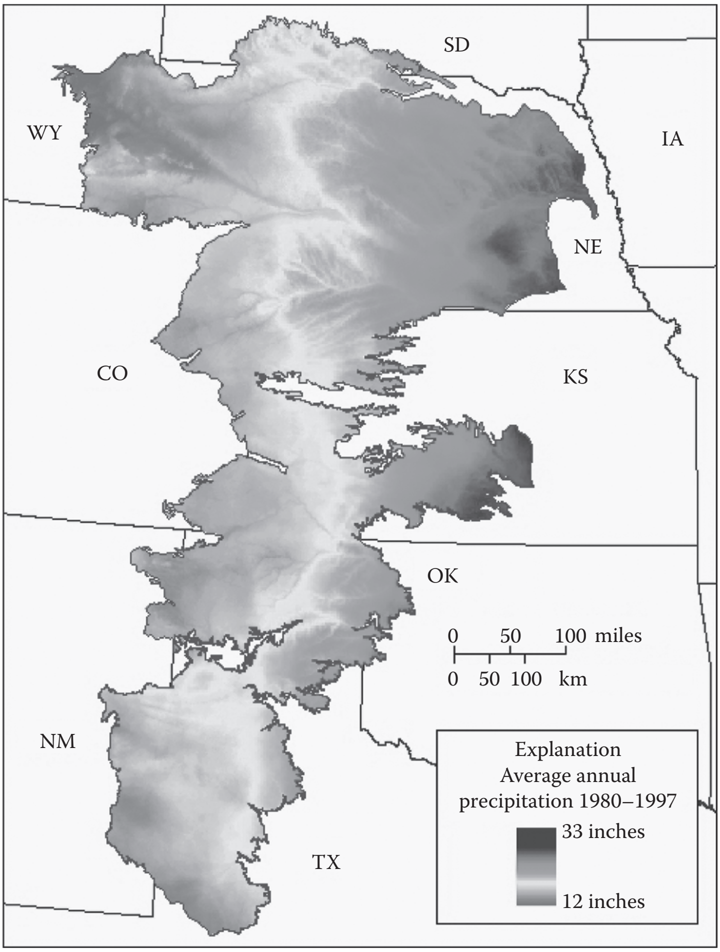


FIGURE 4.2 Precipitation distributions in the High Plains area. (From USGS, High Plains Water-Level Monitoring Study, 2011, http://ne.water.usgs.gov/ogw/hpwlms/physsett.html. Accessed September 30, 2011.)

Oligocene age is the oldest geologic unit included in the aquifer. The Brule Formation is the upper unit of the White River Group and is primarily massive siltstone with beds and channel deposits of sandstone. It includes lenticular beds of volcanic ash, clay, and fine sand. The Brule underlies much of western Nebraska and is included in the aquifer only where it has been fractured or where the formation contains solution openings. Such secondary porosity and permeability are developed only where the Brule crops out or is near the land surface (Figure 4.3; USGS 2011b).

The Arikaree Group of Miocene and Oligocene age overlies the Brule Formation and consists primarily of massive, very fine to fine-grained sandstone. The Arikaree Group crops out in western Nebraska and pinches out to the south and east, as does the White River Group, which includes the Brule Formation. The maximum thickness of the Arikaree is about 305 m in western Nebraska (Weeks and Gutentag 1984; USGS 2011b).

The Ogallala Formation of Miocene age is the principal geologic unit in the High Plains Aquifer and extends to the land surface throughout most of the aquifer area (Table 4.1). The Ogallala Formation consists of unconsolidated gravel, sand, silt, and clay. It also includes caliche, a hard deposit of calcium carbonate that precipitated when part of the groundwater that

TABLE 4.1
The Stratigraphic Columns of the High Plains Aquifer

System	Series	Geologic Unit	Thickness [meters (feet)]	Physical Character
Quaternary	Pleistocene and Holocene	Valley-fill deposits	0–18 (0–60)	Stream-laid deposits of gravel, sand, silt, and clay associated with the most recent cycle of erosion and deposition along present streams. Forms part of High Plains Aquifer when it is hydraulically connected to underlying Quaternary and Tertiary deposits
		Dune sand	0–91 (0–300)	Fine to medium sand with small amounts of clay, silt, and coarse sand formed into hills and ridges by the wind. Forms part of High Plains Aquifer when saturated
		Loess	0–76 (0–250)	Silt with lesser amounts of very fine sand and clay deposited as windblown dust
	Pleistocene	Unconsolidated alluvial deposits	0–168 (0–550)	Stream-laid deposits of gravel, sand, silt, and clay locally cemented by calcium carbonate into caliche or mortar beds. Forms part of High Plains Aquifer when it is hydraulically connected laterally or vertically to Tertiary deposits
Tertiary	Miocene	Ogallala formation	0–213 (0–700)	Poorly sorted clay, silt, sand, and gravel generally unconsolidated; forms caliche layers or mortar beds when cemented by calcium carbonate. Includes units equivalent to the locally used terms “Ash Hollow,” “Kimball,” “Sidney Gravel,” and “Valentine” Members or Formations assigned to the Ogallala Formation or “Group,” and Delmore and Laverne Formations. Ogallala comprises a large part of High Plains Aquifer when saturated
		Arikaree Group	0–305 (0–1000)	Predominantly massive, very fine to fine-grained sandstone with localized beds of volcanic ash, silty sand, siltstone, claystone, sandy clay, limestone, marl, and mortar beds. Includes units assigned to the Hemingford Group of Lugn (1938), Marsland Formation, Rosebud Formation used in South Dakota by Harksen and Macdonald (1969), and Sheep Creek Formation. Also includes units equivalent to Gering Formation, Harrison Sandstone, and Monroe Creek Sandstone. Forms part of the High Plains Aquifer
	Oligocene	White River Group	0–213 (0–700)	Upper unit, Brule Formation, predominantly massive siltstone containing sarrastone beds and channel deposits of sandstone with localized lenticular beds of volcanic ash, claystone, and fine sand. The Brule Formation is considered a part of the High Plains Aquifer only where it contains saturated sandstones or interconnected fractures. Lower unit, Chadron Formation, mainly consists of varicolored, bentonitic, loosely to moderately cemented clay and silt that contains channel deposits of sandstone and conglomerate

Source: Modified from Weeks, J.B. and Gutentag, E.D., In *Ogallala Aquifer Symposium II*, ed. G.A. Whetstone. Texas Tech University, Water Resources Center, Lubbock, TX, 1984.

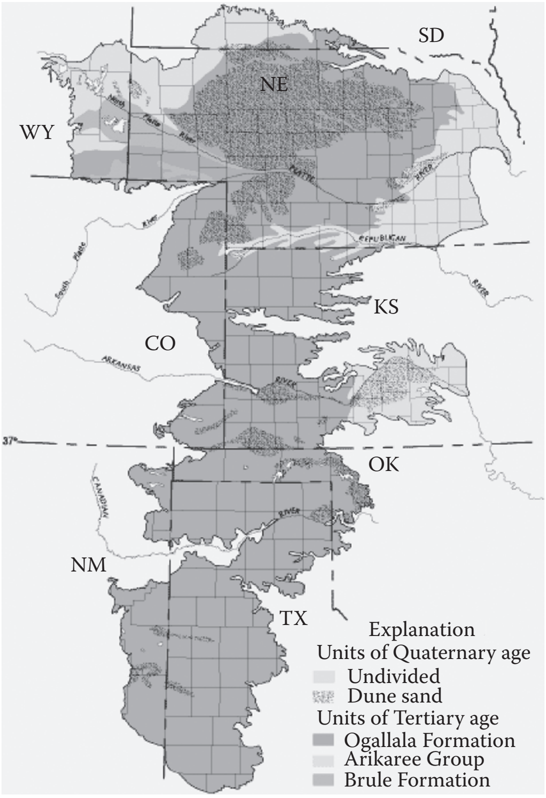

SD
NE
WY
North Platte River
PLATTE
LOUP
REPUBLICAN
RIVER
South Platte River
KS
CO
ARKANSAS
RIVER
37°
OK
CANADIAN
RIVER
NM
TX
Explanation
Units of Quaternary age
Undivided
Dune sand
Units of Tertiary age
Ogallala Formation
Arikaree Group
Brule Formation

FIGURE 4.3 Hydrologic units of the High Plains Aquifer. (From USGS, High Plains Water-Level Monitoring Study, 2011, http://ne.water.usgs.gov/ogw/hpwlms/physsett.html. Accessed September 30, 2011.)

moved through the formation evaporated. During late Tertiary time, the Ogallala Formation was deposited by an extensive eastward-flowing system of braided streams that drained the eastern slopes of the Rocky Mountains over about 347,000 km^2 in eastern Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Weeks and Gutentag 1984; USGS 2011b).

Unconsolidated deposits of Quaternary age overlie the Ogallala Formation. These Quaternary deposits consist of gravel, sand, silt, and clay, much of which is reworked material that was derived from the Ogallala Formation. In places where these unconsolidated deposits are saturated, such as in southeastern Nebraska and south-central Kansas, they compose part of the High Plains Aquifer (Table 4.1). Deposits of loess, deposited as windblown material and consisting mostly of silt with small quantities of very fine-grained sand and clay, overlie the Ogallala Formation or the unconsolidated Quaternary sediments in some locations. Where the loess is thick, it forms the upper confining unit of the High Plains Aquifer. The dune sands of Quaternary age are most extensive in west-central Nebraska, where they cover about 51,800 km^2 and attain a maximum thickness of about 91 m. Saturated dune sands are also part of the High Plains Aquifer south of the Arkansas River in southwest and south-central Kansas. The dune sands are highly porous and, therefore, quickly absorb rainfall that recharges the High Plains Aquifer. Valley-fill deposits along the channels of streams, such as the Platte and the Arkansas Rivers, are also considered to be part of the High Plains Aquifer when they are hydraulically connected with the underlying Quaternary and Tertiary deposits (Weeks and Gutentag 1984). The High Plains Aquifer is underlain by rocks that range in age from Tertiary to Permian.

4.2.3 Population, Land Use, and Agricultural Production

The population of the High Plains area grew more than double from 0.9 million people in 1900 to 2.3 million people in 2000, of which 40% live in the cities with populations greater than 20,000 (U.S. Census Bureau 2000). Many of these cities are located near the major rivers or near the aquifer boundary. Based on USGS (1992) National Land-Cover Data, in the High Plains area 55.6% of land is rangeland, 40.9% agricultural, and 3.5% a combination of wetlands, forest, urban, water, and barren lands. The agricultural lands include 53% row crops (such as sorghum, corn, and cotton), 33% small grains (mostly wheat), and 14% pasture, alfalfa, and fallow lands; and 28% of the agricultural land is irrigated. Crops produced in the High Plains area account for a substantial percentage of the total crop production for the United States. In 1997, the High Plains area yielded 19% of the wheat, 19% of the cotton, 15% of the corn, and 3% of the sorghum of the nation. In addition, the High Plains area also produced about 18% of the total cattle production and an increasing percentage of total swine production in the United States (USDA Census of Agriculture 1998).

4.3 CURRENT STATUS OF HYDROLOGICAL CONDITION AND IMPACTS OF GROUNDWATER DEVELOPMENT

A good knowledge of current hydrological conditions and impacts of historic groundwater development is a key to securing future water supplies for the growing water demands in the region. Large-scale groundwater development in the aquifer has caused great water level drops in SHP, CHP, and in the southern part of the NHP Aquifer. Agricultural recharge has also increased the concentrations of dissolved solids, nitrates, pesticides, and other pollutants, especially in the shallow groundwater. In the area where surface water and groundwater are hydraulically connected, groundwater pumping has also caused depletion of surface water.

4.3.1 Depth to Water

The depth to water in a particular area is the difference between the altitude of land surface and the altitude of the groundwater surface. The generalized depth to water in the High Plains Aquifer in 2000 is shown in Figure 4.4 (McMahon et al. 2007). In most places, the water levels shown are lower than those that existed before widespread irrigation withdrawals began. The depth to water in the High Plains Aquifer is less than 30 m in about one-half of the area of the aquifer and less than 61 m in most of Nebraska and Kansas. The depth to water generally is less near the Platte and the Arkansas Rivers than in areas farther from the rivers, because the rivers are hydraulically connected to the aquifer through the stream valley aquifers that parallel the rivers. The groundwater surface is between 61 and 91 m below the land surface in parts of western and southwestern Nebraska and in parts of southwestern Kansas. The depth to water is as much as 122 m in a small area in southwestern Kansas where development of the aquifer began earlier than in most parts of Kansas; consequently, water-level declines are greater (USGS 2011b; McMahon et al. 2007).

4.3.2 Saturated Thickness and Well Yield

The saturated thickness of an aquifer is the vertical distance between the groundwater surface and the base of the aquifer and is one of the factors that determine the quantity of water that can be pumped from a well. Other factors that affect well yield include well construction and the hydraulic properties of the aquifer. The characteristics of the High Plains Aquifer are listed in Table 4.2.

The saturated thickness of the High Plains Aquifer in 1980 ranged from 0 (where the sediments that compose the aquifer were unsaturated) to about 305 m (Weeks and Gutentag 1984). The greatest saturated thickness is in north-central Nebraska, where the aquifer consists of the Ogallala Formation and overlying dune sands. Locally in southwestern Kansas, dissolution of salt in the

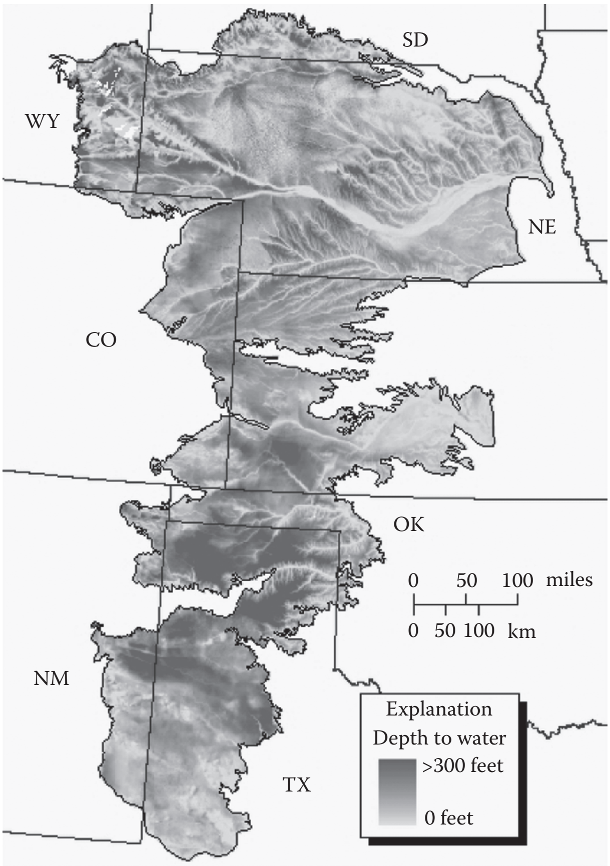


FIGURE 4.4 Depth to water in 2000 in the High Plains Aquifer. (From McMahon, P.B., Dennehy, K.F., Bruce, B.W., et al., U.S. Geological Survey, Professional Paper 1749, Reston, VA, 2007; USGS, High Plains Water-Level Monitoring Study, 2011, http://ne.water.usgs.gov/ogw/hpwlms/physsett.html.)

Permian bedrock that underlies the High Plains Aquifer has resulted in collapse features that were filled with younger sediments. These anomalously thick accumulations of sediments coincide with thick sequences of saturated aquifer materials. The average saturated thickness of the entire aquifer in 2009 was about 57 m. In Nebraska, the average saturated thickness was 104 m, but in Kansas, it was only about 27 m (Table 4.2; McGuire 2011).

Changes in the saturated thickness of the High Plains Aquifer have resulted from groundwater development. Saturated thickness has decreased in most places, but in two areas in south-central Nebraska, recharge to the aquifer from surface-water irrigation, combined with the downward leakage of water from canals and reservoirs, has increased the saturated thickness. In large areas in southwestern Kansas, large-scale irrigation development has decreased the saturated thickness of the aquifer by more than 25%. Decreases of more than 10% in saturated thickness result in a decrease in well yields and an increase in pumping costs because of the increased depth at which the pump must be set to lift the water (Weeks and Gutentag 1984).

The quantity of drainable water in the aquifer can be estimated by multiplying the volume of saturated material by the average specific yield of 0.15 (Weeks and Gutentag 1984; McGuire 2011). According to an estimate by McGuire (2011), there were about 3583 billion m^3 of drainable water stored in the High Plains Aquifer in 2009. About 67% of the drainable water in storage in the entire aquifer is in Nebraska and 11% in Texas. The remaining 22% drainable water is in Colorado, Kansas, New Mexico, South Dakota, Oklahoma, and Wyoming (Table 4.1). Not all drainable water

TABLE 4.2
Characteristics of the High Plains Aquifer

Characteristics	Total	CO	KS	NE	NM	OK	SD	TX	WY
Area underlain by aquifer (km^2)	450,790	38,591	78,995	164,854	24,476	19,037	12,303	91,816	20,720
% of total aquifer area	100	8.6	17.5	36.6	5.4	4.2	2.7	20.4	4.6
% of each state underlain by aquifer	—	14	38	83	8	11	7	13	8
Ave. area weighted saturated thickness for predevelopment (m)	60.9	25.4	33.8	104.2	18.5	43.1	63.3	43.8	55.5
Avg. area weighted saturated thickness in 2009 (m)	56.7	21.3	26.9	104.0	13.9	39.3	63.3	32.6	55.4
Volume of drainable water in storage in 2009 (BCM)	3,583	120	324	2,412	53	120	66	409	79

Source: Modified from Weeks, J.B. and Gutentag, E.D., In *Ogallala Aquifer Symposium II*, ed. G.A. Whetstone. Texas Tech University, Water Resources Center, Lubbock, TX, 1984; USGS, High Plains Water-Level Monitoring Study, 2011, http://ne.water.usgs.gov/ogw/hpwlms/physsett.html. Accessed September 30, 2011; Updated using the data from McGuire, V.L., U.S. Geological Survey Scientific Investigations Report 2011-5089, 13 pp, 2011, http://pubs.usgs.gov/sir/2011/5089/. Accessed August 31, 2011.

in storage within the aquifer can be recovered for use. The quantity of water that can be recovered from the aquifer varies with location, depending on the lithology, saturated thickness, hydraulic conductivity, specific yield of the aquifer at that location, and well construction. Water has been almost completely removed from about 29% of the formerly saturated aquifer material in Texas, whereas the quantity of material dewatered in Nebraska is negligible (Table 4.1).

The greatest yields of water generally are obtained from wells that are completed in coarse-grained aquifer material in places where the saturated thickness of the High Plains Aquifer is great. The potential yield of wells is greater than 47.3 liters per second (L/sec) in most of Nebraska and large parts of Kansas. A well capable of producing 47.3 L/sec can irrigate 51 ha and effectively supply one center-pivot irrigation system. Well yields vary from one formation to the other. Yields from the Brule Formation typically are less than 18.9 L/sec. Wells completed in the Arikaree Group generally do not yield large quantities of water but might yield as much as 22 L/sec in western Nebraska, where the saturated thickness is about 61 m. Well yields from the Brule Formation and the Arikaree Group are greatest where secondary porosity, such as fractures or solution openings, has been developed in the rocks. Well yields from the Ogallala Formation are 63 L/sec from 30 m of saturated sand and gravel in many parts of Kansas and Nebraska but are only 6.3 L/sec from 6 m of saturated sand and gravel in western Kansas (Weeks and Gutentag 1984).

4.3.3 GROUNDWATER FLOW

Water in the High Plains Aquifer generally is under unconfined conditions. Locally, water levels in wells completed in some parts of the aquifer may rise slightly above the regional groundwater surface because of artesian pressure created by local confining beds. The altitude and configuration of the groundwater surface of the High Plains Aquifer are shown in Figure 4.5. The configuration and slope of the groundwater surface are similar to the configuration and slope of the land surface. Water in the aquifer generally moves from west to east, or perpendicular to the contours and in the direction of the arrows shown in Figure 4.5. Water moves in response to the slope of

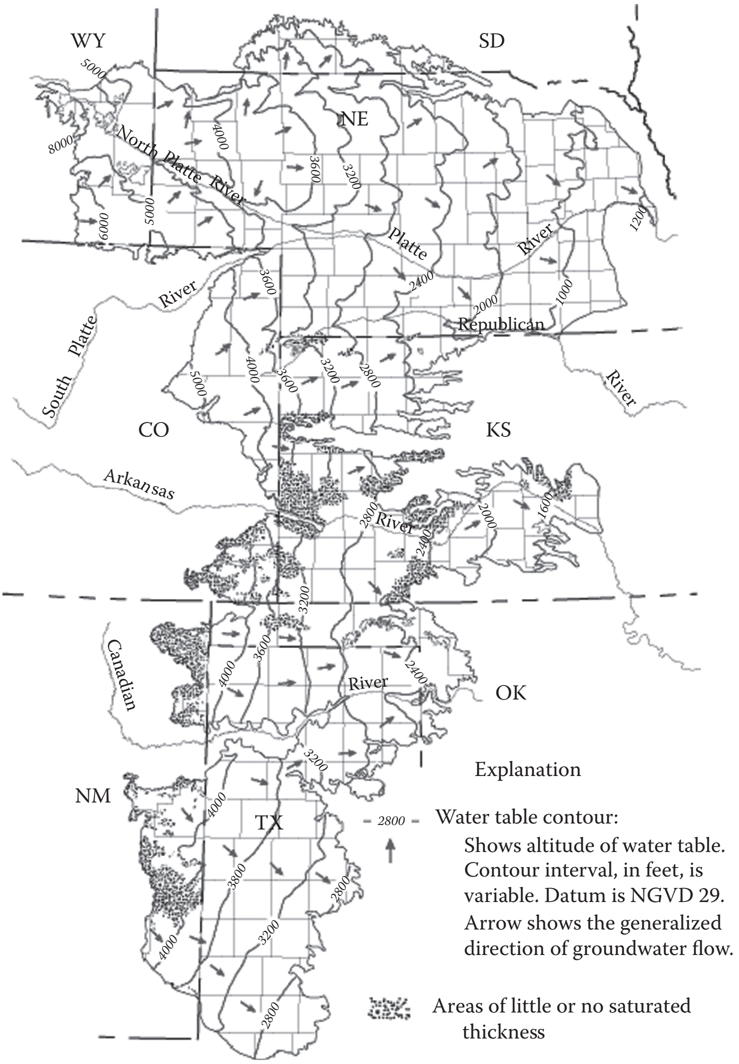

WY
SD
NE
CO
KS
OK
NM
TX
North Platte River
Platte River
South Platte River
Republican River
Arkansas River
Canadian River
8000
6000
5000
4000
3600
3200
2800
2400
2000
1600
1200
1000
3800
Explanation
2800
Water table contour:
Shows altitude of water table.
Contour interval, in feet, is
variable. Datum is NGVD 29.
Arrow shows the generalized
direction of groundwater flow.
Areas of little or no saturated
thickness

FIGURE 4.5 Predevelopment water level contours and direction of groundwater flow. (From Gutentag, E.D., Heimes, F.J., Krothe, N.C., et al., U.S. Geological Survey Professional Paper 1400-B, Reston, VA, 1984; USGS, High Plains Water-Level Monitoring Study, 2011b, http://ne.water.usgs.gov/ogw/hpwlms/physsett.html.)

groundwater surface, which typically averages between 1.89 and 2.84 m/km. On the basis of this average slope and aquifer hydraulic properties, the velocity of water that moves through the aquifer is estimated to average about 0.3 m/day. The spacing of the groundwater level contours is affected by different hydrologic conditions. For example, where contours are widely separated, such as in western Nebraska, the slope of the groundwater surface is gentler than where the contours are more closely spaced. Widespread recharge to the aquifer by infiltration of precipitation through dune sands occurs in western Nebraska, and, thus, the slope of the groundwater surface there is relatively gentle and water will move much slower than in other areas (USGS 2011b).

Where the groundwater level contours cross streams, the configuration of the contours indicates the relation of the water in the aquifer to the water in the stream. For example, where the contours from 975 to 1220 m cross the North Platte River in western Nebraska, the contours bend upstream (Figure 4.5). This upstream flexure indicates that water moves from the aquifer to the stream, and the North Platte River is a gaining stream in this area. By contrast, where the 610 m contour crosses the Platte River in west-central Nebraska, a slight downstream bend in the contour indicates that water is moving from the stream to the aquifer; the Platte River is a losing stream in this area, and the water from the river recharges the aquifer. In southwestern Kansas, the Bear Creek and the Crooked Creek Fault Zones (Figure 4.5) have displaced the High Plains Aquifer and little or no saturated thickness of the aquifer exists on the upthrown side of the faults. In these areas, the groundwater level contours end abruptly at the faults (Figure 4.5; USGS 2011b).

4.3.4 RECHARGE AND DISCHARGE

In an undisturbed groundwater flow system, the amount of water that moves into an aquifer (recharge) is equal to the amount of water that moves out of the aquifer (discharge) over a specific time period, and the flow system is in equilibrium. Prior to development in the High Plains Aquifer, the groundwater level of the aquifer and the quantity of water stored in the aquifer vary little in response to changes in precipitation, stream flow, and the amount and types of vegetation. A groundwater flow system is no longer in equilibrium when the long-term discharge is not equal to the long-term recharge. The altitude of the groundwater surface rises when the recharge rate exceeds the discharge rate and declines when the discharge rate exceeds the recharge rate. Withdrawal of large quantities of groundwater by wells and redistribution of surface water in ditches and canals, all for irrigation purposes, have changed the natural recharge and discharge of the High Plains Aquifer (Weeks and Gutentag 1984).

Recharge to the High Plains Aquifer is primarily by the infiltration of precipitation and locally by the infiltration from streams and canals. Some surface water that is used for crop irrigation also percolates downward and recharges the aquifer. A small quantity of water from the underlying bedrock moves upward and mixes with water in the High Plains Aquifer; this water is also considered to be recharge. The aquifer is recharged at total rates that range between 1.27 and 152 mm/year in Nebraska and Kansas. The rates of recharge are highly variable and range from about 0.3% to 20% of the average annual precipitation in the dry and wet parts of these states. The greatest rates of recharge by precipitation are in areas where dune sand or other highly permeable material is at the land surface. Recharge by infiltration of stream flow usually is greatest when stream flow is high and, thus, provides a large difference between stream and aquifer water levels (Weeks and Gutentag 1984). According to a comprehensive review of published research on the connection between playas and the High Plains Aquifer, most studies indicate that recharge rates are significantly higher beneath playas than in the surrounding nonplaya environment (Gurdak and Roe 2009). Recharge rates, however, do vary from playa to playa. Characteristics that affect recharge include playa size and depth, size of a playa's drainage area, depth of the clay that lines the basin, depth of sediment that has accumulated in the basin, subsurface sediment between the playa and the aquifer, and depth of the groundwater surface.

Natural discharge from the High Plains occurs at springs, seeps, streams, and as evapotranspiration by plants. Where the groundwater surface is near the land surface, groundwater can evaporate directly. Transpiration rates are greatest along stream valleys where deep-rooted salt cedar, willows, cottonwoods, and sedges grow. Where the High Plains Aquifer is locally underlain by permeable bedrock and the groundwater surface in the aquifer is higher than that in the bedrock, small amounts of water move downward from the aquifer into the bedrock (Weeks and Gutentag 1984).

Large quantities of water are withdrawn from the aquifer by wells, and in some areas large amounts of water discharge from the aquifer to streams. For example, a study was done during 1975 to determine how much of the flow of the Platte River in Nebraska was derived from groundwater. The annual gain in stream flow within Nebraska was about 3.7 billion m^3, most of which was groundwater discharge from the High Plains Aquifer to the river. Large quantities of surface water are diverted from the Platte River and used for irrigation; thus, the amount of groundwater discharge to the river probably was significantly greater than the measured gain in stream flow.

Most of the discharge from the High Plains Aquifer is by withdrawals from wells, and practically all of the water withdrawn is used for irrigation purposes (Weeks and Gutentag 1984).

4.3.5 GROUNDWATER QUALITY

The chemical quality of water in the High Plains Aquifer is affected by many factors. These factors include the chemical composition and solubility of aquifer materials, the increase in dissolved-solids concentrations in groundwater in areas where the water discharges by evapotranspiration, and the chemical composition of water that recharges the aquifer. Groundwater generally contains smaller concentrations of dissolved minerals near recharge areas where the residence time of the water in the aquifer has been short, and, therefore, dissolution of aquifer minerals has been less. The water generally is more mineralized near discharge areas because residence time has been longer and more dissolution of minerals has taken place.

The dissolved-solids concentration in groundwater is a general indicator of the chemical quality of the water. Dissolved-solids concentrations in groundwater from the High Plains Aquifer are less than 500 milligrams per liter (mg/L) in most of Kansas and Nebraska but locally exceed 1000 mg/L in both states. The limit of dissolved solids recommended by the U.S. Environmental Protection Agency for drinking water is 500 mg/L. Most crops can tolerate water in which the dissolved-solids concentration is 500 mg/L or less. In places with well-drained soils, many types of crops can tolerate water with a dissolved-solids concentration between 500 and 1500 mg/L. In southwestern and south-central Kansas, the High Plains Aquifer overlies Permian bedrock that contains bedded salt. Where circulating groundwater has dissolved some of this salt and the mineralized water has subsequently moved upward into the High Plains Aquifer, the dissolved-solids concentration of the water in the High Plains Aquifer is greatly increased. Also, dissolved-solids concentrations are generally greater near streams where water from the High Plains Aquifer discharges. Groundwater near the streams is shallow enough to be transpired by plants or to be evaporated directly from the soil. Concentrations of dissolved solids in the groundwater are increased by the evapotranspiration process. Rates of transpiration are greatest where deep-rooted phreatophytes, such as sedges, cottonwood, willows, and salt cedar, grow.

Excessive concentrations of sodium in water adversely affect plant growth and soil properties, and constitute salinity and sodium hazards that may limit irrigation development. Sodium that has been concentrated in the soil by evapotranspiration and ion exchange decreases the tillability and permeability of soil. Areas of high or very high sodium hazard occur in parts of Kansas. Sodium hazard is evaluated by the sodium adsorption ratio, which relates the concentration of sodium to calcium plus magnesium; if this ratio is high, then the sodium can destroy any clay in the soil and thus affect soil structure. Concentrations are less than 25 mg/L in most of Nebraska and northern Kansas. Concentrations are greatest in southwestern Kansas where evapotranspiration rates are high and in south-central Kansas where the High Plains Aquifer overlies Permian bedrock that contains saline water derived from the partial dissolution of salt beds. Sodium concentrations are high along the Platte and the Republican Rivers where the evapotranspiration rates also are high. Salinity and sodium hazards are generally low in Nebraska where the High Plains Aquifer primarily consists of sand and gravel, which contain few sodium-bearing minerals (Gurdak et al. 2009).

Excessive fluoride concentrations are a widespread problem in water from the High Plains Aquifer. Some of the fluoride is derived from the dissolution of fluoride-bearing minerals in parts of the aquifer that contain sand and gravel, such as the Ogallala Formation. Extremely large concentrations (2–8 mg/L) of fluoride are reported where the aquifer contains volcanic ash deposits or where it is underlain by rocks of Cretaceous age. Large concentrations of fluoride in drinking water cause staining of teeth, but fluoride is not a concern in irrigation water (Gurdak et al. 2009).

The generally shallow depth of the groundwater surface in the High Plains Aquifer makes water in the aquifer susceptible to contamination. Application of fertilizers and organic pesticides to cropland has greatly increased since the 1960s, thereby increasing the amount of potential contaminants present in the soil. Increased concentrations of sodium, alkalinity, nitrate, and triazine (a herbicide) have been found in water that underlies small areas of irrigated croplands in Nebraska and Kansas. Of the 132 wells sampled during 1984–1985 in Nebraska, 43 had measurable concentrations (>0.04 micrograms per liter, μg/L) of the herbicide atrazine. Increased concentrations of 2,4-dichlorophen-oxyacetic acid (2,4-d, a pesticide) were found in water that underlies rangeland in a small part of the Great Bend area of the Arkansas River in Kansas (Gurdak et al. 2009).

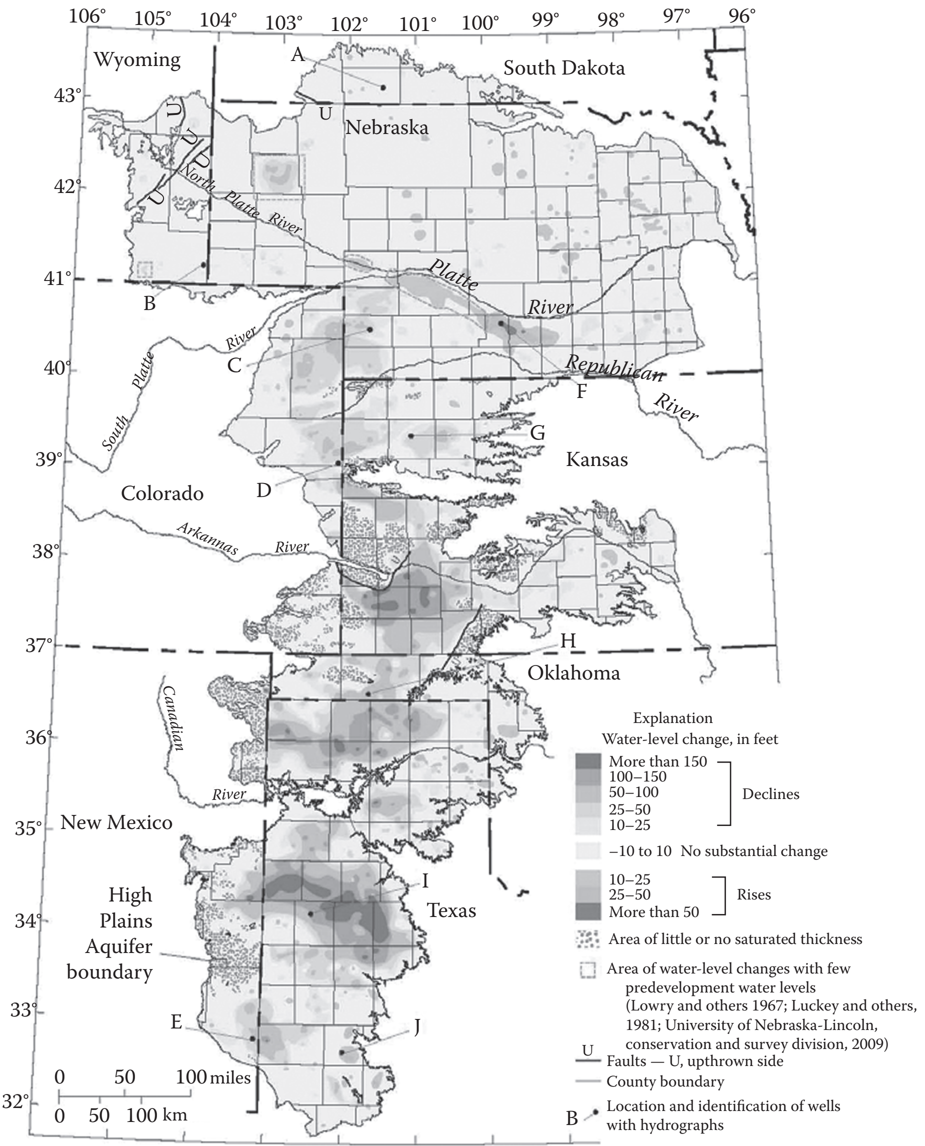
4.3.6 IMPACT OF GROUNDWATER DEVELOPMENT

4.3.6.1 Water Level Drop: Depletion of the Aquifer

Decline of the groundwater level started after the implementation of irrigation development in the High Plains Aquifer. The acreage irrigated with groundwater increased from 0.85 million ha in 1949, to 2.47 million ha in 1959, to 3.64 million ha in 1969, and to 5.54 million ha in 1980 (Gutentag et al. 1984). For the period 1980–2005, irrigated acreage had minor fluctuations ranging from 5.14 million ha (2002) to 6.27 million (2005) (McGuire et al. 2003).

In 2000, almost 97% of the total withdrawals (66.2 million m^3/day or an annual total of 24.2 billion m^3) from the High Plains Aquifer were used for irrigation; the remaining 3% were used for public, industrial, domestic, and other uses. Nebraska, Texas, and Kansas accounted for 88% of the total withdrawals, which was almost entirely used for irrigation (Maupin and Barber 2005). SHP started experiencing water level declines by 1940, the CHP by 1950, and the NHP by 1960. From predevelopment until 1980, the highest water level drops in Texas were around 61 m, and the maximum declines in CHP of southern Kansas exceeded 31 m but were registered only in two small areas in that region. Water level declines of more than 15 m were detected in different small sections of CHP of southwestern Kansas, the north central panhandle of Texas, the central panhandle of Texas, and the central panhandle of Oklahoma (McGrath and Dugan 1993). During the period of 1980–1999, considering water levels from 4818 wells in the High Plains Aquifer, the water level variation ranged from 10 m rise to 20 m decline (McGuire 2001). The average area-weighted water level decline was 1 m as compared with 3 m experienced during the period from predevelopment to 1980. South of the Canadian River in New Mexico and Texas and an area southwest of Kansas had water level declines of more than 18 m, the highest in the High Plains Aquifer (McGuire 2001).

From predevelopment until 2009, water level declines of more than 3, 7.6, and 15.2 m were present, respectively, in 26%, 18%, and 11% of the aquifer. Only 2% of the aquifer registered water level increases of more than 3 m. From predevelopment to 2009, the aquifer has had a water storage decline of around 338 billion m^3. As a result, the total drainable water storage in the aquifer was approximately 3583 billion m^3 (McGuire 2011). Figure 4.6 depicts groundwater level changes from predevelopment to 2009. This figure shows that the highest water level declines occurred in Texas and the southwest portion of Kansas. Water level rising occurred in Nebraska perhaps as a result of irrigation using surface water as well seepage from the irrigation network. The three states exclusively located in the NHP, Nebraska, South Dakota, and Wyoming, have had virtually no change in average saturated thickness since predevelopment. The larger saturated thickness, larger recharge rates, smaller consumptive irrigation requirements, and later development of groundwater irrigation have contributed to less depletion of groundwater storage in the region. The acreage-weighted average saturated thickness in Colorado, Kansas, and Oklahoma, which covers most of the CHP area, was less than 30 m or about 85% of the predevelopment saturated thickness. The average saturated aquifer thickness in New Mexico and Texas in the SHP was less than 29 m or less than 80% of the predevelopment saturated thickness. The larger declines in saturated thickness in the SHP than the other High Plains Aquifer areas can be attributed to earlier groundwater development and less recharge (Dugan et al. 1994).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North Platte River
Platte River
South Platte River
Republican River
Arkansas River
Canadian River
High Plains Aquifer boundary
0 50 100 miles
0 50 100 km
Explanation
Water-level change, in feet
More than 150
100–150
50–100
25–50
10–25
Declines
−10 to 10 No substantial change
10–25
25–50
More than 50
Rises
Area of little or no saturated thickness
Area of water-level changes with few predevelopment water levels (Lowry and others 1967; Luckey and others, 1981; University of Nebraska-Lincoln, conservation and survey division, 2009)
Faults — U, upthrown side
County boundary
Location and identification of wells with hydrographs

Base from U.S. Geological survey digital data, 2001, 1:2,000,000
Albers equal-area projection
Standard parallels 29° 30' and 45° 30', central meridan – 101°

FIGURE 4.6 Water level changes from predevelopment to 2009. (From McGuire, V.L., U.S. Geological Survey Scientific Investigations Report 2011-5089, 13 pp, 2011, http://pubs.usgs.gov/sir/2011/5089/. Accessed August 31, 2011.)

4.3.6.2 Deterioration of Water Quality and Soil Salinity

Groundwater sustainability of an aquifer depends on both water quantity and water quality. In the High Plains Aquifer, deep groundwater has been recharged during the past several thousand years, while shallow groundwater, near the groundwater surface and underneath irrigated land, has been recharged during the last 50 years. The water of the High Plains Aquifer has been affected by irrigation farming activities. Agricultural recharge has increased the concentrations, mainly in the shallow groundwater, of dissolved solids, nitrate, pesticides, and other pollutants.

The transport of chemicals from land surface to water could take decades to centuries; however, natural depressions could reduce the transport time of pollutants to the groundwater surface (Gurdak et al. 2009).

For the period 1999–2004, the U.S. Geological Survey's National Water-Quality Assessment Program (NAWQA) offered the first systematic effort to assess water quality of the High Plains Aquifer in three subdivisions, NHP, CHP, and SHP, respectively (Gurdak et al. 2009). According to the study, based on the maximum contaminant level (MCL) established by the federal national drinking standards, the Ogallala Formation of the SHP has the poorest domestic well water quality, while the central Ogallala Formation in the CHP and NHP had the better water quality. Most of the exceedance values in the MCL of national standards were for arsenic, dissolved solids, fluoride, iron, manganese, and nitrate. Arsenic values exceeded primary federal standard values (MCL = 10 μg/L) in at least one water sample of each of the hydrogeologic units except for the CHP. The average value of arsenic concentration in the aquifer was close to 4.91 μg/L, and the highest percentage, around 59%, of arsenic concentration above the MCL was on the SHP (McMahon et al. 2007).

The median nitrate concentration values remained very similar, around 2 mg/L as nitrogen, for the period 1930–1970, and increased to almost 3 mg/L for the period 1980–1990 (Litke 2001; McMahon et al. 2007). For the period 1999–2004, the average nitrate concentration values for the three regions were close to 2.8 mg/L, with a maximum value of 20.3 mg/L in the CHP region (Ogallala formation). Atrazine, deethylatrazine, and chloroform were the most commonly detected pesticides and volatile organic compound, respectively; however, none of them exceeded primary drinking water standards (McMahon et al. 2007).

Elevated salinity in irrigation water is greatest in the southern part of the High Plains Aquifer. The total dissolved-solids concentrations of 3% of samples exceeded 2000 mg/L, which means severe salinity restrictions should be applied if the water is used for irrigation. No salinity restrictions were exceeded for samples from the northern part of the High Plains Aquifer. About half of the samples from the central and southern parts of the aquifer could be characterized as having slight to moderate salinity with restrictions on the use of irrigation water (McMahon et al. 2007).

The USDA (1988) Soil Conservation Service identified the High Plains region as an area of high potential for water and soil salinity problems based on spatial scales of river basins or watersheds and salt indicators, which include Total Dissolved Solids (TDS) and chloride in waters and salts in surface soils and geologic formations. Soil salinity is more widespread in the northern Plains than anywhere else in the United States. Salinity adversely affects crop growth in the region's most northern states. Saline conditions in the root zone severely affect nearly 10% of the northern Plains landscapes (USDA 1996). The areas of the saline-affected soils were based on the presence of a horizon with greater than 4 dS/m within 50 cm of the land surface. The electrical conductivity estimates of the soils followed the saturated paste method of the Soil Survey Staff (1995).

4.3.6.3 Effects on Surface Water and Ecosystem

Groundwater depletion can drastically affect rivers and streams, such as turning once perennial rivers into ephemeral ones (Stromberg et al. 1996). Groundwater pumping in the High Plains Aquifer has resulted in a decrease in base flow or discharge of the aquifer into the streams, especially in Kansas and Nebraska. During extreme droughts such as the ones in the 1950s, heavy groundwater pumping could even turn a gaining stream into a losing stream. This sudden decrease threatened the riparian ecosystem. Usually, the first species to be affected by the drop in groundwater levels are the water-sensitive plants, like some wetland and riparian plants. Such plants as juvenile *Salix gooddingii*, juvenile *Populusfremontii*, and juvenile *Fraxinusvelutina* only have a range of about 1.8 m change in depth to groundwater. This means that these plants will not be able to survive if the groundwater level drops more than 1.9 m from the surface (Stromberg et al. 1996). Younger plants are also generally more affected by the lack of groundwater than the older plants (Stromberg et al. 1996). Currently, in some part of the High Plains Aquifer, groundwater has dropped more than 45 m from predevelopment conditions (McGuire 2011). Hence, in areas around the High Plains Aquifer, such riparian ecosystems have already been destroyed. Similar conditions have been observed throughout the western United States. Since these species have such a narrow range of tolerance for water table changes, any decrease in groundwater surface can result in a decrease in the biodiversity of the ecosystem. In addition, as groundwater levels drop and native species begin to die, new exotic, nonnative species will begin to invade the ecosystem. These invasive species have a higher tolerance for a decrease in groundwater and can better adapt to this environment. Consequently, an invasion by exotic species greatly exacerbates the decrease of biodiversity in an ecosystem (Stromberg et al. 1996).

4.4 GROUNDWATER BUDGET, GROUNDWATER AVAILABILITY, AND DFCs

To determine the DFC, we need to know the current groundwater storage and groundwater budget. However, not all the groundwater stored in the aquifer will become available due to technological, environmental, economic, and legal constraints.

4.4.1 Groundwater Budget and Availability

Assuming that the groundwater budget in an aquifer system is in long-term equilibrium, under predevelopment conditions, inflow (recharge) into the aquifer system is approximately equal to outflow (discharge). The quantity of water stored in the aquifer system is constant or varies about some average condition in response to annual or longer-term climatic variations (Alley et al. 1999). The groundwater budget can be described in terms of rates (or volumes over a specified period of time) as (Alley et al. 1999; Sheng 2011)

$$\sum Q_i^{in} - \sum Q_i^{out} = \Delta S, \tag{4.1}$$

where Q_i^{in} and Q_i^{out} are, respectively, inflow and outflow rates of the groundwater system and ΔS is the change in storage, reflecting annual or longer-term climatic variations. Under natural conditions, inflow (recharge) includes (1) areal recharge from precipitations through an unsaturated zone to the groundwater surface (Q_r); (2) recharge from losing streams, lakes, and wetlands (Q_s); and (3) subsurface (groundwater) inflow or interbasin exchange (Q_{fin}): while outflow (discharge) includes (1) discharge to streams, lake, wetlands, and springs (Q_d); (2) evapotranspiration (Q_e); and (3) subsurface outflow (Q_{fout}) (ASCE 1987; Alley et al. 1999; Sheng 2011).

Such equilibrium can be broken by pumping and artificial recharge using imported water, treated wastewater, or storm water. If only considering the effects of pumping, the groundwater budget can then be written as

$$\sum Q_i^P = \sum Q_i^{in} - \sum Q_i^{out} - \Delta S. \tag{4.2}$$

As a dynamic system, pumpage Q_i^P will be achieved by increasing inflow Q^{in}, for example, by increased seepage, decreasing outflow $Q_i{}^{out}$, decreasing storage S, or a combination of all three.

The inflows can be further expanded as

$$\sum Q_i^{in} = Q_r + Q_s + Q_{fin}, \tag{4.3a}$$

$$\sum Q_i^{out} = Q_d + Q_e + Q_{fout}. \tag{4.3b}$$

All the inflow and outflow terms on the right sides of the above equations are the sum of each component over the whole basin during a specific time period of interest. For example, Q_r is the recharge from precipitation through infiltration and deep percolation. It is controlled by land cover, hydrological properties of geological materials, intensity, and duration of precipitation. Irrigation (crops, consumptive uses, irrigation scheduling) and urbanization (pavement) affect soil moisture, infiltration, deep percolation, and eventually influence recharge to the aquifer. Native vegetation covers have been replaced by invasive plants, in turn affecting recharge, especially mountain front recharge. Climate variations could have altered precipitation patterns, resulting in variable recharge. Other terms also vary to different degrees in response to human activities and climate variability. Therefore, groundwater budget terms inherit a great deal of uncertainty due to the heterogeneity of materials and lack of historical data. It should be noted that the above equations only consider water quantity; they do not consider the effects of water quality on water availability.

Once pumping starts, the aquifer system will adjust itself and try to reach a new equilibrium after some time, called the aquifer system response time, which is defined as the time taken for the water level and storage changes throughout the aquifer system to become negligible after an increase or decrease in supply withdrawal (Walton 2011) or the time taken to full capture (Bredehoeft and Durbin 2009). The aquifer response time can range from days to centuries or more (Bredehoeft et al. 1982; Sophocleous 2000; Alley et al. 2002; Bredehoeft and Kendy 2008), depending on many factors, such as aquifer system dimensions, aquifer transmissivity and storativity, confining layer storage, confining layer leakage, aquifer system boundary conditions, and well location and penetration.

Even though the groundwater budget can be calculated or estimated with acceptable accuracy, water availability or sustainability has proved to be an elusive and multifaceted concept to define in a precise manner and with universal applicability. *Water availability* is not a simple function of the quantity and quality of water in an aquifer system but is also constrained by the physical structures, laws, regulations, and socioeconomic factors that control its demand and use (Alley and Leake 2004). Therefore, determining *groundwater availability* means more than calculating the volume of groundwater underlying a particular area or within an aquifer. One must also consider that some of the water may not be economically recoverable or of poor quality as well as the fact that groundwater is connected to the rest of the hydrologic system. Groundwater withdrawals can and usually do affect the amount (and quality) of surface water. For example, depletion of a small part of the total volume of groundwater in storage (sometimes only a few percent) can have substantial and undesirable effects on the availability of surface water, which becomes the limiting factor in the development of the groundwater resource (Alley 2007). The Texas Water Development Board (TWDB) defines groundwater availability as the effective recharge plus the amount of water that can be recovered annually from storage over a specified planning period without causing irreversible harm such as land-surface subsidence or water-quality deterioration (Muller and Price 1979; Mace et al. 2006).

A number of other terms have been used to describe groundwater availability. One of them is *groundwater sustainability,* which was defined by Alley et al. (1999) as the "development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences." The term *safe yield* has been used and amended to quantify sustainable groundwater development (Lee 1915; Meinzer 1920, 1923; Williams and Lohman 1949; Bear and Levin 1967; Bear 1979; Domenico and Schwartz 1990; Fetter 1994; Sophocleous 1997, 2000). The term *groundwater mining* or *groundwater overdraft* usually refers to a prolonged and progressive decrease in the amount of water stored in a groundwater system (Reilly et al. 2008), for example, in heavily pumped aquifers in arid and semiarid regions as the study area, especially in Texas and Kansas. The relative contributions of changes in storage, changes in recharge, and changes in discharge evolve with time. The initial response to withdrawal of water is changes in storage. If the system can come to a new equilibrium, the changes in storage will stop and inflows will again balance outflows, for example, the balanced groundwater budget in Nebraska.

Groundwater availability can range from nothing to all of the drainable water from an aquifer. Therefore, any method for determining groundwater availability should recognize such characteristics. Quantifying groundwater availability requires an intersection of policy and science: policy to define socioeconomic and environmental goals and science to estimate the actual amount of water that can be produced based on the socioeconomic goals (Mace et al. 2001).

4.4.2 DESIRED FUTURE CONDITIONS

The concept of desired conditions (DCs) as the social, economic, and ecological attributes that management strives to attain is well established (IEMTF 1995). DCs and desired future conditions (DFCs), pioneered by the U.S. Forest Service as part of its planning process in the 1970s and 1980s, have evolved over time as a result of criticisms and different applications (Leslie et al. 1996; Sutter et al. 2001). In a science context, the term tends to imply that DCs can be expressed specifically and measurably; however, in the planning process of most resource management agencies, it often implies a more broad description from which more specific objectives are tiered. In the application of planning processes, the term generally implies a timescale that is relatively long-term (e.g., >15 years), for example, 50 years for water resources planning in Texas. In other applications, however, such a timescale may or may not be applied (Bennetts and Bingham 2007). Planning processes generally include a hierarchy of goals and objectives, ranging from a broad vision or mission statement down to specific objectives or targets within a timescales ranging from long (e.g., into perpetuity) to short (e.g., annual or less). Two additional elements in the planning process are goals expressed in terms of desired resource conditions and goals expressed in terms of management strategies or activities intended to achieve those desired resource conditions.

In the 1970s, the noticeable depletion of the Ogallala Aquifer was the beginning of the public policy concern about the future condition of groundwater resources. The greatest levels of depletion have occurred in northern Texas and west-central Kansas. Certain portions of these areas have presented water level declines of more than 45.7 m, with decreases, especially in the Texas portion, of more than 50% in the saturated thickness of the aquifer. A great portion of the aquifer is beneath the Nebraska Sandhills, which has not been considerably exploited because irrigation farming is not economically feasible (McGuire and Fischer 1999; Peterson et al. 2003; McGuire 2009).

The Ogallala Aquifer is the largest aquifer in North America. The aquifer is shared by eight states, which makes its management complicated. These states have different interests and laws and regulations. Texas groundwater law is based on the “rule of capture,” which some interpret as a “use it or lose it” rule. Under this rule, land owners are entitled to the water underneath their land (Kromm and White 1992; Verchick 1999). Nebraska and Oklahoma apply the general rules of the correlative rights doctrine (groundwater shared by the owners overlying the aquifer, extracted water applicable under the overlying land, and groundwater rights are usufructuary). The rest of the other states utilize the prior appropriation doctrine, which in a similar fashion to that of surface water protects water users on the basis of seniority in time (Gardner et al. 1997).

The states have been implementing regulations to manage groundwater. For instance, Kansas, New Mexico, and Colorado established policies to deny new water pumping permits if it is demonstrated that water availability in surrounding wells could be affected (Peterson et al. 2003). In 1972, Kansas authorized the creation of groundwater management districts (GMDs) to have more direct control over groundwater management. In 1991, the northwest Kansas GMD 4 implemented the “zero depletion” policy, which limited pumping to not exceed the aquifer natural recharge (Sophocleous 2000).

In September 2005, the Texas legislature passed House Bill 1763, which brought significant changes to groundwater resources management in Texas. Among the most important changes are the following: besides defining their groundwater availability, GMDs will be in charge of developing DFCs; groundwater conservation districts (GCDs) are tasked to define groundwater availability for regional water planning processes; and groundwater districts will issue permits based on groundwater availability (Mace et al. 2006). DFCs serve as management goals and provide answers as to how the aquifer would look in the future (Sheng et al. 2011).

In 2008, the North Plains GCD in Texas proposed to establish an Ogallala Aquifer DFC for Dallam, Hartley, Moore, and Sherman Counties; and Hansford, Hutchinson, Ochiltree, and Lipscomb Counties in Groundwater Management Area 1 (GMA-1): at least 40% of the aquifer storage to be remaining in 50 years for the area of Dallam, Hartley, Moore, and Sherman Counties and at least 50% of the aquifer storage to be remaining in 50 years for the area of Hansford, Hutchinson, Ochiltree, and Lipscomb Counties within the district. The district proposed two DFCs because the uses or conditions for the aquifer within the district differ substantially from one geographic area to another (North Plains Groundwater Conservation District 2008). Then, managed available groundwater will be determined by the TWDB based on the DFCs. The impacts of DFCs on other districts will be evaluated.

Mittelstet et al. (2011) (cited in President's message of April 2011, AWRA Water Blog<awramedia.org/mainblog/page7/>) compared two approaches to the administration of groundwater law on a hydrologic model of the North Canadian River, an alluvial aquifer in northwestern Oklahoma. Oklahoma limits pumping rates to retain 50% aquifer saturated thickness after 20 years of groundwater use. The Texas Panhandle GDC's rules limit pumping to a rate that consumes no more than 50% of saturated thickness in 50 years, with reevaluation and readjustment of permits every 5 years, using a hydrologic model (MODFLOW). Their results show that Oklahoma's approach initially would limit groundwater extraction more than the Texas GCD approach, but the Texas GCD approach would be more protective in the long run. Both the Oklahoma and Texas Panhandle GCD approaches would deplete alluvial base flow at approximately 10% development. Results also suggested that periodic reviews of permits could protect aquifer storage and river base flow.

In sum, DFCs set goals for retaining fresh groundwater storage in the aquifer within a time frame (50 years) based on current hydrological conditions and legal framework. To achieve those DFC goals, GMDs/state agencies also develop management strategies or activities for implementation. Some DFCs target the sustainable development of natural resources, such as the "zero depletion" policy in Kansas, others do not. Determination of DFC relies on multiple factors, including physical constraints of natural resources (aquifer and groundwater), and technology (irrigation methods), and social–economical, legal, and institutional constraints.

4.4.3 CONSTRAINTS

How much groundwater is available for use depends upon how these changes in inflow and outflow affect the surrounding environment (physical and technical constraints) and what the public defines as undesirable effects on the environment (socioeconomic and institutional constraints). In determining the effects of pumping and the amount of water available for use, it is critical to recognize that not all the water pumped is necessarily consumed. For example, not all the water pumped for irrigation is consumed by crop evapotranspiration. Part of the irrigated water returns to the groundwater system as infiltration (irrigation return flow). Most other uses of groundwater are similar in that some of the water pumped is not consumed but is returned to the system (Alley et al. 1999). Thus, it is important to differentiate between the amount of water pumped and the amount of water consumed when we estimate future water availability, develop management strategies, and set up DFC goals.

4.4.3.1 Physical Constraints

Two key elements should be considered in the estimation of the amount of groundwater that is available for use. First, the use of groundwater and surface water must be evaluated together as a system. This evaluation includes all of the water available from changes in groundwater recharge, from changes in groundwater discharge, and from changes in storage for different levels of water consumption as shown in Equation 4.2. Second, because any use of groundwater changes the subsurface and surface environment (i.e., the water must come from somewhere), the trade-off between groundwater use and changes to the environment should be determined and a threshold should be set at which the level of change becomes undesirable. In conjunction with a system-wide analysis of the groundwater and surface-water resources this threshold can then be used to determine appropriate limits for consumptive use (Alley et al. 1999).

System-wide hydrologic analyses typically use numerical models to aid in estimating water availability and the effects of extracting water on the groundwater and surface-water system. If constructed correctly, the computer models attempt to represent the complex relations among the inflows, outflows, changes in storage, movement of water in the system, and possibly other important features using mathematical equations. As a mathematical representation of the system, the models can be used to estimate the response of the system to various development options and provide insight into appropriate management strategies. However, a computer model is a simplified representation of the actual system, and the judgment of water-management professionals is required to evaluate model simulation results and plan appropriate actions (Alley et al. 1999).

Extensive pumping of groundwater for irrigation has led to groundwater-level declines in excess of 46 m in parts of the High Plains Aquifer in Kansas, New Mexico, Oklahoma, and Texas. These large water-level declines have led to reductions in the saturated thickness of the aquifer exceeding 50% of the predevelopment saturated thickness in some areas. Lower groundwater levels cause increases in pumping lifts. Decreases in the saturated thickness result in declining well yields. Surface-water irrigation has resulted in water-level rises in some parts of the aquifer system, such as along the Platte River in Nebraska.

A long delay between pumping and its effects on natural discharge from the High Plains Aquifer is caused by the large distance between many of the pumping wells and the location of the springs and seeps that discharge from the groundwater system. The SHP is perhaps the best known example of significant, long-term nonequilibrium for a regional groundwater system in the United States. That is, water levels continue to decline without reaching a new balance (equilibrium) between recharge to and discharge from the groundwater system. When the groundwater level declines, less water will be available for irrigation and the cost for pumping will increase as pumping lift increases. As a result, dryland acreage tends to increase. Figure 4.7 shows that from 1972 to 2000 the dryland acreage share in 16 counties in the Southern Texas High Plains increased as the groundwater levels dropped. In summary, in the SHP and CHP areas, DFCs will mostly be limited by saturated thickness and depth to water, while in the northern part of the NHP, DFCs will mostly likely be limited by water-quality concerns instead of water quantity within the planning horizon.

4.4.3.2 Economic Constraints

Agricultural economics can be a limiting factor to set up DFC goals. Most economic factors, such as crop prices, ad energy, land, fertilizer, labor, and equipment costs, are independent of water resources, but the cost of pumping is closely related to groundwater availability, controlled by depth to water (pump lifting) and well yield. As the groundwater level declines (increasing pumping lift), energy consumption (gas/electricity) is proportional to pumping lift. Depth to water and well yield could become important constraints to future agricultural economics and development. Advanced irrigation technology requires high capital investment for irrigated agricultural production, while at the same time there are clearly economic benefits from the improved technology, such as reduced labor costs and more crop revenue per unit of water applied (Upendram and Peterson 2007). What are the incentives for water users to conserve water? As suggested by Upendram and Peterson (2007), the public funds could be used more effectively directed to programs that ensure a reduction in overall water depletion, such as the purchase and retirement of water rights. Therefore, DFC can

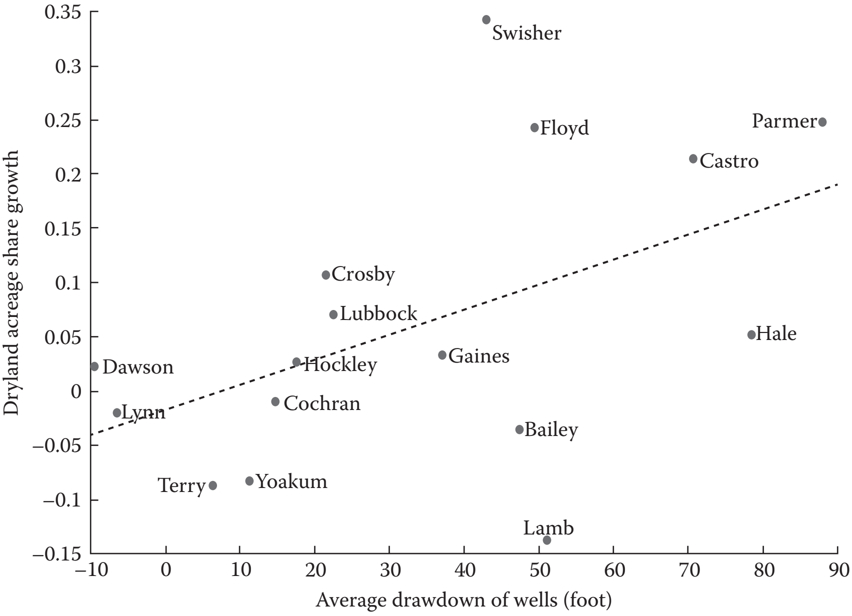

FIGURE 4.7 Dryland acreage expands as groundwater level declines.

also be constrained by water users' behavior in terms of economic benefits and availability of public funds for water conservation.

4.4.3.3 Effects of Irrigation Technology

Advances in irrigation technology have resulted in water-use efficiency and high crop production per unit of water applied. Irrigation efficiencies vary for different types of systems, depending upon application rates, crops, soil type, and field slope, but are typically in the range of 40%–60% for surface or gravity flow systems, 75%–85% for improved surface or gravity systems, 75%–85% for sprinkler systems, and 90%–98% for low energy precise application (LEPA) systems used with furrow dikes (Sloggett and Dickason 1986). Different water conservation techniques to maximize water resources are summarized in Table 4.3. Figure 4.8 shows changes in crop production in the Texas High Plains from 1950 to 2010, which reflect the effects of multiple factors, including advances in irrigation technology, groundwater available for irrigation, costs for pumping, fertilizer, labor, prices of crops, drought, and others. Further study is on the way to identify relationship among the farmers' decision on crop selection, irrigation technology, and groundwater availability (see Section 4.4.4 for details). Conventionally, people anticipated that the overall consumptive uses/depletion of natural groundwater storage would be reduced by the adoption of new irrigation technologies or conservation measures. However, recent research findings of Upendram and Peterson (2007) indicated that an improvement in irrigation efficiency by adapting new irrigation technology can result in either more or less water consumption, with the direction of impact depending on the changes in irrigated acreage and crop choice following the efficiency improvement. In contrast to widely held beliefs, Ward and Pulido-Velazquez's (2008a) study results in the Upper Rio Grande Basin indicated that water conservation subsides are unlikely to reduce water use under conditions that occur in many river basins. Adoption of more efficient technologies could reduce valuable return flows and limit aquifer recharge; therefore, conservation programs that target reduced water diversions or applications do not necessarily guarantee water savings. To achieve DFC goals, by reducing depletion by adopting more efficient irrigation technologies, we should design and

TABLE 4.3
Maximize Total Water Resources—Rainfall and Irrigation

Reduce crop constraints

- Drought-tolerant crops (grain sorghum vs. corn)
- Deep rooted crops
- Rotation of crops—spread water demand

Prevent rainfall runoff and soil surface evaporation

- Land forming techniques
  - Leveling
  - Contour farming
  - Terracing
- Furrow diking
- Crop residue—reduced or no-till

Soil water accounting

- Soil profile full of water prior to peak crop demand
- Hydrologic frequency analysis—rainfall probability relative to crop demand

Irrigation

- Accommodate critical crop growth periods
- Ratio of irrigated to dryland becomes a function of early rainfall
- Staggered planting dates to stagger water demand
- Variety selection for drought stress
- Application systems
  - Eliminate nonevapotranspiration losses
    - Water distribution losses, runoff, deep percolation
  - Furrow systems—short runs
  - Spray—sprinkler systems: large droplet size, applicator close to soil
  - Low energy precision application systems
  - Subsurface drip irrigation

Source: Modified from Lyle, W.M. and Bordovsky, J.P., Paper 85-2602, ASAE, St. Joseph, MI, 1985.

implement technical, accounting, and institutional measures that accurately track and economically reward reduced water depletion (Ward and Pulido-Velazquez 2008a).

4.4.3.4 Legal and Institutional Constraints

In the High Plains, state laws that regulate the development of groundwater vary from one to another. Oklahoma and Texas are the only two states that recognize private ownership of groundwater, while other six state laws dedicate water to the people of the state. Some set specific depletion caps, while others only require that water must go to "beneficial uses." In all states, a well registration or permitting system exists. In several states, there is a limit on the minimum spacing between wells.

In Colorado, one must obtain a permit to use groundwater, which is considered property rights and can be bought and sold independently of the land upon which the well rests. The Colorado Groundwater Commission is in charge of issuing and changing water permits. It divided the groundwater in Colorado into two districts: the NHP Designated Basin and the SHP Designated Basin. Designated groundwater is defined by the Colorado legislature as "groundwater which in its natural course would not be available to and required for the fulfillment of decreed surface rights, or groundwater in areas not adjacent to a continually flowing stream wherein groundwater

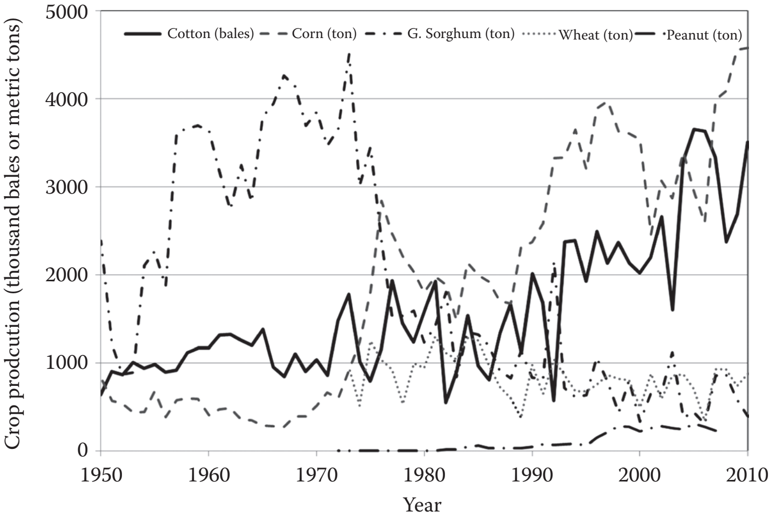

FIGURE 4.8 Irrigated crop production form the Texas High Plains (District 1-N and 1-S). (Data from http://quickstats.nass.usda.gov/, http://www.nass.usda.gov/Statistics_by_State/Texas/Publications/Historic_Estimates/he_corn.pdf, http://www.nass.usda.gov/Statistics_by_State/Texas/Publications/Historic_Estimates/he_cotton.pdf, http://www.nass.usda.gov/Statistics_by_State/Texas/Publications/Historic_Estimates/he_sorghum.pdf.)

withdrawals have constituted the principal water usage for at least fifteen years" (Colorado Statutes, Title 37 Article 90). These districts can put additional rules regarding groundwater management into place. Since 1990, permits have been issued with the policy that no permit will be issued for a new well if it is projected that the well will deplete the aquifer within a 4.8 km (3 mile) radius by 40% within 100 years (McGuire et al. 2003).

In Kansas, anyone with a permit or a vested right can use groundwater for nondomestic purposes. Landowners must "use the water for beneficial purposes" (McGuire et al. 2003). Five GMDs are in charge of regulating nondomestic water use and they can propose regulations that do not conflict with state law. Of these governing bodies, some follow the idea of "safe yield" and others follow the idea of "allowable depletion." "Safe yield" is the concept that total groundwater withdrawal in the district must be a certain percentage of the aquifer recharge in that radius. "Allowable depletion" is the concept that total groundwater withdrawal in the district must not deplete the aquifer in that radius by more than a specific amount in a specific time (Sophocleous 1998; McGuire et al. 2003; Kansas Department of Agriculture 2009).

In Nebraska, groundwater is a public resource. One has the right to use "a reasonable amount of the groundwater under their land for beneficial use on that land" (McGuire et al. 2003). The Nebraska Department of Natural Resources (NDNR) is in charge of groundwater withdrawals. In the early 1970s, the legislature created 23 Natural Resource Districts (NRDs), which have the authority to manage groundwater use. Each NRD is required to have a groundwater management plan approved by the NDNR, which outlines what the NRD will do to manage depletion and quality concerns in its area. In areas where there is no NDNR governance, residents follow the Nebraska correlative rights doctrine that states that residents must share when groundwater supplies are limiting (McGuire et al. 2003).

In New Mexico, water rights in six groundwater basins are based on the prior appropriation governed by the state engineer (New Mexico Office of the State Engineer 2005). In general, the state engineer approves most permits for domestic use. For nondomestic use, however, the state engineer will approve permits only if these four criteria are met: "(1) no objections are filed,

(2) unappropriated water exists in the basin, (3) no infringement on the water rights of prior appropriators occurs, and (4) it is not detrimental to the public welfare or the water conservation goals of the State" (McGuire et al. 2003). In addition, water rights are bought and sold independently of the land upon which the well sits. As long as the state engineer approves, water rights can be sold for out-of-state use (McGuire et al. 2003). The state engineer determines whether unappropriated water exists in the basins by monitoring water-level declines within a 23–65 km^2 area, depending on aquifer properties, around the site of a proposed new appropriation. If the annual water-level decline exceeds 0.76 m, the state engineer will not approve the permit because the rate of decline is considered excessive (Templer 1992; Ashley and Smith 1999).

In Oklahoma groundwater management policy is based on the reasonable use doctrine. The groundwater is owned by the landowners whose properties overlie the aquifer. The Oklahoma Water Resources Board (OWRB) grants licenses for withdrawing water from the aquifer. The amount of water withdrawn is determined by the OWRB and varies from region to region. This amount is determined by the maximum amount of water that can be withdrawn and still secure the availability of water at least 20 years from the time of the license; hence, the specific amount of water is uniquely calculated for each region. This amount is adjusted yearly when each license holder must check in with the OWRB and report how much water they pumped and set limits for the amount of water allowed for the next year (OWRB 2002; McGuire et al. 2003).

In South Dakota, water as a public resource is managed by the South Dakota Department of Environment and Natural Resources (SDDENR). The SDDENR works with the Water Management Board (WMB), a group of citizens, to manage groundwater resources. However, water can be withdrawn once a permit has been approved. The state also sets a specified amount of water that can be withdrawn. Generally, the amount of water withdrawn does not exceed the natural recharge rate. However, most of the land overlying the High Plains Aquifer in South Dakota lies within the boundary of either the Pine Ridge or Rosebud Indian Reservations, and the tribes assert the right to control the development and use of groundwater resources within reservation boundaries (South Dakota, Codified Laws, Title 46; South Dakota Administrative Rules, Article 74:02). All permits, other than irrigation permits, can be transferred to out-of-state (McGuire et al. 2003).

In Texas, groundwater is regarded as a public resource as it is still in the aquifer. However, once the groundwater is withdrawn, it is specific to the landowner. Groundwater can be sold to other locations, including out-of-state. No landowner can purposefully withdraw groundwater for "malicious reasons or to willfully waste the water." The GCD can enact some limitations on the groundwater withdrawal rate, the total amount withdrawn, and the well spacing (State of Texas Statutes, Chapters 35 and 36). Fourteen GCDs regulate to a varying extent more than 81% of the area that overlies the High Plains Aquifer in Texas (TWDB 2010). No permits are needed for wells that withdraw less than 94.6 m^3/day (or 25,000 gallons/day) or for domestic/livestock wells (McGuire et al. 2003; TWDB 2010).

In Wyoming, groundwater management policy is based on prior appropriation. Wyoming law mandates that all natural waters be the property of the state. Permits are given out to users for beneficial use. There is no specific limit on the amount of water that can be withdrawn. If the user would like to change any aspect of the permit, the user must first appeal to the state. No permits are needed if the out-of-state transfer is less than 1.23 million m^3/year (McGuire et al. 2003; Wyoming State Engineer's Office 2005).

4.4.4 The Linkage between Aquifer Hydrology and Water User Behavior

Evaluating alternative DFC-based management plans requires accurate predictions of future aquifer conditions. One of the many challenges facing groundwater policy analysts is to model the complex interactions between water-user behavior and aquifer conditions. This section presents a critical review of the state of the research in this area and points out a new direction for future work.

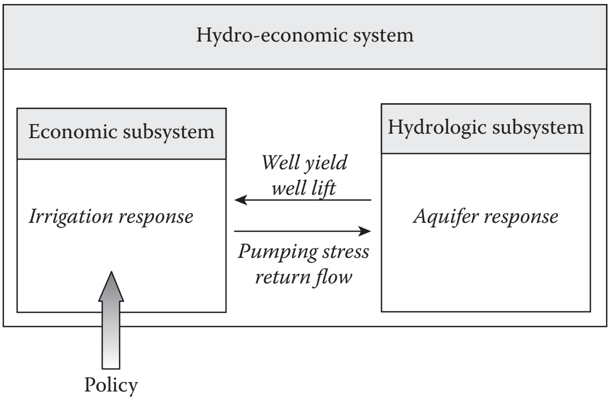

FIGURE 4.9 A conceptual framework for water policy evaluation.

4.4.4.1 A Conceptual Framework

A general characteristic of human exploitation of natural resources is that the behavior of the resource users and resource stock are dynamically interdependent. While resource exploitation perturbs the physical equilibrium of the resource stock, the change in that stock's properties, such as quality, quantity, and availability, can conversely affect the resource user's cost–benefit equation, resulting in a change in utilization of the resource. In the case of groundwater use, pumping alters the groundwater level and well yield, which in turn changes the water user's future pumping costs and water demand.

To be more specific, consider the evaluation of alternative management plans to achieve a predetermined set of DFCs. Figure 4.9 illustrates the various channels thorough which a management plan influences the aquifer system. Suppose that the management plan is aimed at reducing the pumping of water for irrigation by way of introducing incentives or regulations. The resulting alterations in the pumping for irrigation will change the speed at which the groundwater surface declines. This will change the pumping lift and well yield facing the irrigator, which in turn will affect future water-use decisions. Failing to account for this dynamic effect can lead to biased estimations of future aquifer conditions.

The extant hydrological models for simulating future aquifer conditions do not explicitly account for this dynamic process. Rather, future groundwater demands are frequently estimated separately and then incorporated into the hydrological model as an independent external force. The future conditions simulated in this manner are subject to prediction errors, which can lead to misinformed decisions. These limitations are illustrated below with the groundwater policy analysis framework presently adopted in the state of Texas.

4.4.4.2 The Hydrology-Centered Modeling Approach

The TWDB has developed sophisticated hydrological models to facilitate water management and planning. In particular, a MODFLOW-based aquifer model, a groundwater availability model (GAM) (Blandford et al. 2008), has been developed for the southernmost part of the Ogallala Aquifer underlying portions of Texas and New Mexico. GAM has served as the basis for the regional water planning groups in the Texas High Plains to develop DFCs and evaluate alternative water management plans.

The TWDB has developed separate estimation methods for municipal, industry and mining, steam electric power, agricultural irrigation, and livestock (TWDB 2011). Here we focus only on agricultural irrigation water use because it accounts for over 95% of the water use in the Texas Ogallala Aquifer. In GAM future irrigation water demands are estimated in two steps. Historic water demands are first estimated, and then projected into the planning period to generate the required future water demands. Estimation of historic irrigation water demands is based on satellite imagery data and irrigation surveys conducted by the National Agriculture Statistics Service (NASS 2007). The acreage planted for each crop under irrigation is estimated for each county using remote sensors or satellite sensors. Because the water applications in each crop depend on the irrigation technologies used, the crop acreage data are combined with the NASS irrigation survey data to generate county-level water use. Future water demands are then obtained using a simple linear extrapolation method, with minor adjustments made in accordance with the discrepancy between previous predictions and actual observations (TWDB 2002, 2007).

The approach described above evidently oversimplifies the water user's decision-making process. Indeed, it lacks a model representing the water user's decision-making process under a constantly changing environment dictated by a variety of economic, hydrological, and policy factors. Although updating the extrapolative model periodically does help improve the predictive power of the model in the short run, it is inadequate for long-run policy analysis—such as water planning over a 50 year horizon to achieve the 50/50 groundwater management goal.

4.4.4.3 The Economic Analysis of Groundwater Policy

Most economic analyses of groundwater policy have been cast in a rational choice model, in which the water users are assumed to maximize an economic objective subject to a set of economic, hydrologic, and institutional constraints. Solving the optimization model produces a set of decisions to be made by the water user, including the quantity of water demanded. Using this approach, a large body of literature has developed to evaluate groundwater policy in the Texas portion of the Ogallala Aquifer (Arabiyat 1998; Feng 1992; Johnson 2003; Wheeler 2005). Parallel research has been conducted for other parts of the United States (e.g., Peterson and Ding 2005; Scheierling et al. 2006; Ward and Pulido-Velázquez 2008b).

This approach renders the analyst a great deal of modeling flexibility, permitting detailed information to be analyzed in complex, large-scale optimization models. However, it also forces the analyst to assume—sometimes in an arbitrary fashion—producer behavior, rather than discover it empirically from past data. Consequently, conclusions often are drawn on a case-by-case basis. Arbitrary behavioral assumptions in these hydroeconomic models limit their prediction power.

Meanwhile, these optimization models tend to oversimplify the evolution of the aquifer system. The complex aquifer system is frequently represented by a few equations with variables defined at the county level, leaving unexploited a great deal of hydrological information available.

4.4.4.4 Toward a Holistic Approach

The two types of analyses reviewed above have each contributed in their own ways to our ability to understand the aquifer system's future conditions, leaving substantial gaps that can be closed only by combining their respective strengths to form a unified framework for policy analysis. The best approach for assessing groundwater management plans should take explicit account of the dynamic interactions of the hydrologic and economic systems. And such a holistic approach should be taken not only in estimation or calibration of the model, but also in use of the model to predict future conditions, on which we elaborate below.

The usefulness of a model depends ultimately on its ability to explain the historic data and predict the future behavior of the system under concern. A holistic approach for model development can improve the performances of the economic and hydrologic models simultaneously. Consider the economic model first. To estimate groundwater use requires a model explaining the cropping and irrigation technology adoption patterns. A large body of econometric analyses has been conducted to understand the producer's irrigation technology and crop choice, and the estimation method is well established (Baerenklau and Knapp 2007; Caswell and Zilberman 1985; Green et al. 1996; Lichtenberg 1989; Plantinga et al. 1999; Shah et al. 1995; Wu and Brorsen 1995; Wu and Segerson 1995). Most of these models, however, treat resource conditions in an oversimplified manner. In groundwater-related studies, the typical approach is to construct a few variables summarizing the hydrologic conditions facing the water user and include them as explanatory variables in the regression. The most frequently used proxies are well depth and fuel cost (e.g., Caswell et al. 1990; Negri and Brooks 1990). This approach in essence takes hydrologic conditions as exogenous variables independent of economic activity, ignoring the complex dynamic process described above. Hydrological models can generate a wealth of detailed hydrologic data, providing an opportunity to improve these econometric models. While most of the land use models are developed at the county level, for example, hydrological models can generate hydrological data at a much more refined level. Incorporating such data into the econometric model is bound to improve estimation precision.

Hydrological models, such as the GAM described above, can also be improved if more accurate water-use data are used for model calibration. Because the econometric model takes full account of various forces of influence on water-use decisions, it is bound to provide a more accurate estimation of groundwater demand than the methods presently adopted by hydrologists. Incorporating the econometrically estimated groundwater use data into hydrological models, therefore, will improve these models' predictive power.

The procedures described above build on existing models and therefore are easy to implement. They essentially require a data-sharing protocol between the hydrologist and the economist. A more challenging yet more interesting approach is to completely integrate econometric estimation and hydrologic model calibration. That is, they are executed in a unified computer program so that the interchange of the hydrologic and economic data described above can be automated and iterated. This approach will maximize the performance of the two models but require a much close collaboration between the economist and the hydrologist.

Once the hydrologic and economic models are developed, they can be used to simulate future groundwater conditions to examine whether a proposed water management plan can achieve DFCs. The integrated approach can improve the simulation results. Unlike in the simple extrapolative model mentioned above, the econometrically estimated water-use model allows water-use patterns to change in response to a variety of economic and environmental conditions. The policy analyst, then, will be able to run the simulation under a large number of contingencies, allowing a robust test of water management plans.

4.5 SUMMARY

The High Plains Aquifer is a vital water resource of great importance to the economy of the High Plains region. It supplies water for the region's crop, livestock, and meat processing industries. Because the High Plains Aquifer receives limited and slow recharge, especially in the SHP and CHP areas, the High Plains economy is dependent on a finite water resource.

Historical overdraft of groundwater has caused large water level drops, especially in the SHP and CHP. In Texas, a decline of 71 m from the predevelopment water level was observed in 2009. Heavy groundwater pumping and intensive agricultural production have also caused deterioration of groundwater quality, which in turn further reduced groundwater availability, as the high salinity causes damage to crops and soil structures. Heavy groundwater pumping has also caused depletion of streams adjacent to the shallow aquifer, as groundwater pumping alters the hydraulic connection between the aquifer and the stream.

To assure future water supplies, different measures and policies have been implemented. One concept is to set up DFCs for the High Plains Aquifer. Though the term DFC may mean different things for different people, the planning process generally reflects a hierarchy of goals and objectives, ranging from a broad vision or mission statement down to specific objectives or targets within a timescale. Two additional elements include goals expressed in terms of desired resource conditions and goals expressed in terms of management strategies or activities intended to achieve those desired resource conditions. DFCs set by Texas, Kansas, and Oklahoma intend to slow down or curtail the ongoing depletion of groundwater in some highly stressed areas. Some DFCs tend to create more sustainable development, while others may not. DFCs are affected by multiple factors, including physical constraints of the aquifer, irrigation technology, economic, and legal/institutional constraints. To develop effective DFC goals for future groundwater development, we need an integrated model taking account of the hydrological, economic, and institutional forces that influences groundwater availability. In this chapter, we propose such a framework linking the existing hydrological model to a new econometric model to assess alternative groundwater management plans for achieving DFC goals.

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ABBREVIATIONS

BMPs	Best management practices
CHP	Central High Plains
DFC	Desired future condition
GAM	Groundwater availability model
GCD	Groundwater conservation district
GMA	Groundwater Management Area
GMDs	Groundwater management districts
MCL	Maximum contaminant level
NAWQA	National Water-Quality of Assessment Program
NDNR	Nebraska Department of Natural Resources
NGVD	National Geodetic Vertical Datum
NHP	Northern High Plains
NRD	Natural Resource District
OWRB	Oklahoma Water Resources Board
SDDENR	South Dakota Department of Environment and Natural Resources
SHP	Southern High Plains
TWDB	Texas Water Development Board
USGS	U.S. Geological Survey
WMB	Water Management Board

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5 Competition between Environmental, Urban, and Rural Groundwater Demands and the Impacts on Agriculture in Edwards Aquifer Area, Texas

Venkatesh Uddameri and Vijay P. Singh

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5.1 INTRODUCTION

The Edwards Aquifer is a prolific limestone formation in central Texas and includes the Edwards and associated limestones. The aquifer spans across 12 counties (Figure 5.1) and serves as the main water supply to nearly 2 million residents. The major cities sustained by the aquifer include the city of San Antonio and the metropolitan areas of San Marcos and south Austin. South-central Texas is one of the fastest-growing areas in the nation. Between 2000 and 2010, the population in the region increased by approximately 20% (U.S. Census 2010). Austin and San Antonio were ranked first and second, respectively, among the large cities on Forbes' best places for jobs list in 2010 (Fisher 2011). The Edwards Aquifer is a shared resource that not only drives economic growth, but also sustains the unique ecological flora and fauna of the Texas hill country. The aquifer is home to several endangered and threatened species, such as the Fountain Darter and the Texas Blind Salamander (Fridell 2008). The south-central part of Texas is also the prime agricultural area in the state that depends on the Edwards Aquifer resources. The major crops grown in the area include vegetables, hay, cotton, and cereal crops, such as barley, corn, sorghum, and wheat, which are important to meet the food and fiber requirements of the state and the nation. Because it is a water-scarce region, the competition for water between agricultural, urban, and ecological interests is intense; therefore, the Edwards Aquifer resources are highly regulated and managed using a complex set of policies and protocols (EAA 2011).

Water is a major natural constraint that limits growth in semiarid regions, such as Texas. The Edwards Aquifer region lies at the cusp of two major physiographic regions—the Low Western

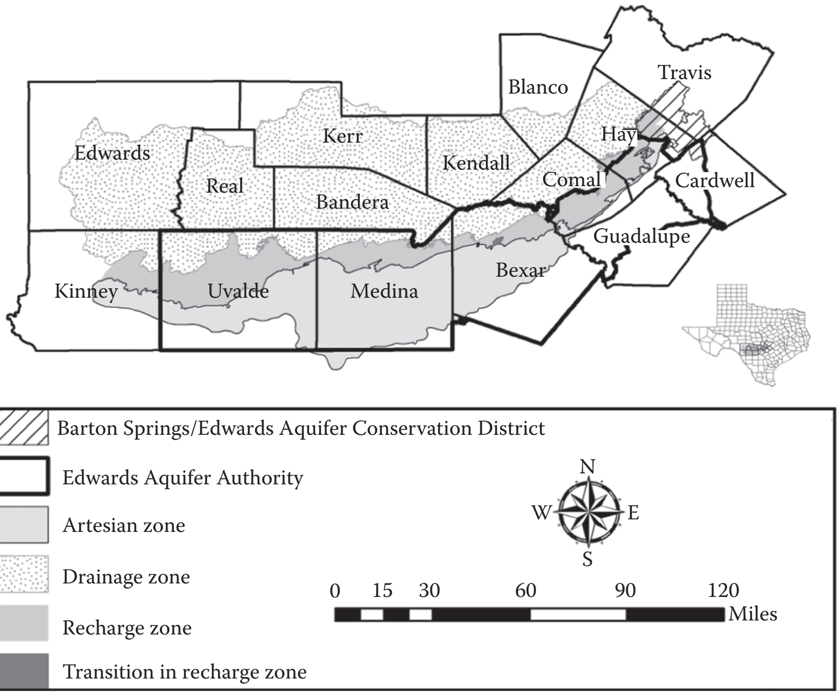

Edwards
Kerr
Blanco
Travis
Hays
Kendall
Real
Bandera
Comal
Cardwell
Guadalupe
Bexar
Kinney
Uvalde
Medina
Barton Springs/Edwards Aquifer Conservation District
Edwards Aquifer Authority
Artesian zone
Drainage zone
Recharge zone
Transition in recharge zone
N
W
E
S
0 15 30 60 90 120
Miles

FIGURE 5.1 Edwards Aquifer area and jurisdictional boundaries of the Edwards Aquifer Authority and the Barton Springs/Edwards Aquifer Conservation District.

Plains and the Gulf Coastal Plains—and crosses through the Edwards Plateau and south-central climatic regions of the state (Bomar 1995). The climate in the region varies from semiarid to subtropical, humid zones (Larkin and Bomar 1983). As such, the rainfall is highly erratic and is characterized by prolonged droughts or years of extremely high rainfall. These problematic climatic patterns, coupled with the increasing need for continuous and sustained water supplies to meet the urban demands and ecological requirements, pose a unique threat to the viability of agriculture in the region. The transfer of water from the agricultural sector to meet the municipal and industrial demands is becoming increasingly common in Texas and is likely to continue in the future (TWDB 2007). According to the south-central region water planning group's projections, the municipal demands in the Edwards Aquifer region are likely to increase by 47% in the year 2060 from the current needs of approximately 370,000 AFY. On the other hand, the water demand for irrigation is projected to decrease by 27% from the current usage of 380,000 AFY and some of this will be used to offset the growing municipal needs (TWDB 2011). These shifts in water uses will increase the risk of food security in the region because agricultural products have to be imported in greater quantities. There is a renewed interest in using agricultural produce for biofuel production. Many crops produced in the Edwards Aquifer region, such as wheat, corn, and sorghum, have lower carbon emissions when compared with gasoline (McCarl 2006). Therefore, the possibility of using crops in the region to produce biofuels further exacerbates the potential risks to the self-reliance and food security of the region.

Understanding the nature and the extent of the risk to the agricultural activities in the Edwards Aquifer region and the steps that can be taken to mitigate the impacts, particularly in an altered climate regime of the future, is an important aspect of topical interest to land and water planners in the region and the nation. The overall goal of this chapter is to undertake a historical evaluation of rural to urban land use changes along with an assessment of the available water supplies and the salient hydrologic factors and regulatory frameworks controlling their use, to understand the agricultural shifts in the region. This understanding of the historical trends is used to evaluate the potential risks to agriculture, particularly in the context of an altered climate in the future.

5.2 EDWARDS AQUIFER: HYDROGEOLOGICAL SETTING

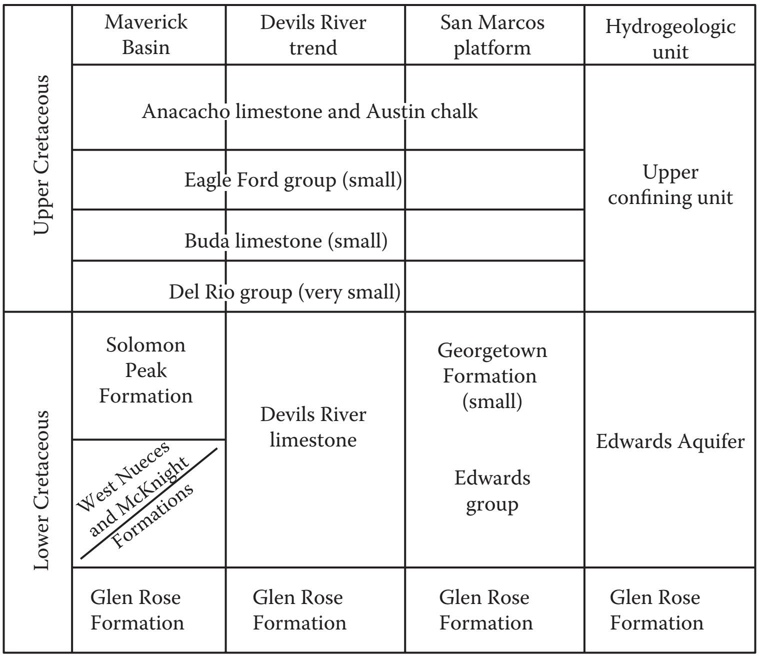
The Edwards Aquifer is composed of regionally extensive carbonate rocks and is one of the most permeable aquifers in the world. The Edwards Aquifer is divided into two segments, namely, the San Antonio segment, which extends from a groundwater divide near the city of Brackettville in Kinney County to a groundwater divide near the city of Kyle in Hays County (Figure 5.1). The San Antonio segment includes all or parts of Uvalde, Medina, Bexar, Comal, and Hays Counties. The San Antonio segment is approximately 180 mi long and 5–40 mi wide and discharges into the Comal Springs and San Marcos Springs (Hamilton et al. 2008). The northern portions of the aquifer extend to the outcrop regions of the Edwards rocks, while the "bad water line" (i.e., 10,000 mg/L of total dissolved solids or the fresh water–saline water interface) is assumed as the southern boundary (Lindgren et al. 2004).

The Barton Springs segment extends from Kyle to south Austin in Travis County (Figure 5.1), covering an area of approximately 130 mi^2 and discharging into the Barton Springs and Cold Springs in the vicinity of Austin, Texas (Barrett and Charbeneau1997). The Barton Springs segment is bounded by a hydraulic divide on the south along Onion Creek and by the Colorado River in the north. The Mount Bonnell fault is taken as the western boundary and the aquifer is considered to end at the bad water line along the east (Scanlon et al. 2003).

Four depositional provinces were formed during the Lower Cretaceous era—the central Texas platform on the Edwards Plateau, the Maverick Basin, the Devils River trend, and the San Marcos platform (Maclay 1995). Three of these provinces (Maverick Basin, Devils River trend, and San Marcos platform) occupy much of the present-day Edwards Aquifer. The Edwards Aquifer is underlain by the Trinity Aquifer, which is composed of sediments from the Glen Rose limestone formation deposited during the early portions of the Lower Cretaceous era and, for the most part, is overlain by Anacacho limestone, Austin chalk, Eagle Ford group, Buda limestone, and Del Rio clay deposits from the Upper Cretaceous era (Figure 5.2). The recharge zone of the Edwards Aquifer occurs along the northern boundary where it outcrops uncomfortably (Puente 1978).

Abbott (1975) has described the geochemical evolution of the Edwards Aquifer. Because it is a karst system, the aquifer is characterized by a highly heterogeneous and anisotropic hydraulic conductivity distribution. Hovorka et al. (1998, 2004), Mace and Hovorka (2000), and Halihan et al. (2000) present information pertaining to the matrix, fracture, and conduit permeabilities and suggest the locations of major conduits. The conduit development is more pronounced in the deeper portions of the aquifer, which tend to be saturated, than the shallower portions, which may only retain water for relatively short periods. The geochemistry of the aquifer sediments was initially composed of aragonite, calcite, dolomite, and gypsum. These minerals have been replaced by calcite within the aquifer (Hovorka et al. 2004). The reader is referred to Lindgren et al. (2004) and the above references for additional details pertaining to the hydrogeologic conceptualization of the Edwards Aquifer. In addition, literature reviews pertaining to the Edwards Aquifer have been compiled by Menard (1995) and Esquilin (2004) and provide useful hydrogeochemical information.

The aquifer thickness ranges from about 450 ft near the recharge zone in Bexar, Comal, and Hays Counties to about 1100 ft in Kinney County. The flow of water in the aquifer is highly heterogeneous and anisotropic and, to a large extent, depends on the extent of karstification. Generally speaking, the flow in the aquifer occurs under unsaturated conditions in caves by turbulent flow in solution-enlarged conduits (Gale 1984). Worthington (2001) reports an average velocity along the conduits of about 6000 ft/day. The hydraulic conductivity and transmissivity obtained using the pump tests reflect the combined effects of the matrix, fracture, and conduit permeability, and each varies by several orders of magnitude. The transmissivity in the recharge area is less than 430,000 ft^2/day and that in the confined portions of the freshwater zone is estimated to range from 430,000 to 2,200,000 ft^2/day. The transmissivity near the fresh water–saline water boundary is extremely



	Maverick Basin	Devils River trend	San Marcos platform	Hydrogeologic unit
Upper Cretaceous	Anacacho limestone and Austin chalk			Upper confining unit
	Eagle Ford group (small)			
	Buda limestone (small)			
	Del Rio group (very small)			
Lower Cretaceous	Solomon Peak Formation	Devils River limestone	Georgetown Formation (small)	Edwards Aquifer
	West Nueces and McKnight Formations		Edwards group	
	Glen Rose Formation	Glen Rose Formation	Glen Rose Formation	Glen Rose Formation

FIGURE 5.2 Hydrostratigraphic structure of the Edwards Aquifer Formation. (Modified from Lindgren, R.J., Dutton, A.R., Hovorka, S.D. et al., Conceptualization and simulation of the Edwards Aquifer, San Antonio region, TX. Reston, VA: U.S. Geological Survey, 2004; Maclay, R.W. Geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas. Reston, VA: U.S. Geological Survey, 1995.)

low and on the order of 100 ft^2/day (Maclay and Land 1988). The specific yield of the aquifer ranges from 0.05 to 0.2 in the San Antonio segment and from 0.005 to 0.06 in the Barton Springs segment (Maclay and Land 1988; Senger and Kreitler 1984). As can be seen, the aquifer is capable of accommodating and transmitting significant amounts of water, but has limited storage capabilities when compared with clastic aquifer formations.

5.3 RECHARGE AND DISCHARGE

The recharge to the Edwards Aquifer occurs in the north and northeastern parts of the Balcones fault zone, where streams lose flow. The recharge from the losing creeks is considered to be a major recharge mechanism in the Barton Springs segment of the aquifer as well (Barrett and Charbeneau 1997). Due to direct precipitation on the aquifer, the diffuse recharge is estimated to be about 15% of the total annual recharge (Scanlon et al. 2003). The regional groundwater flow in the San Antonio segment consists of a flow from the unconfined formation through the confined formation to eventual discharge into the San Marcos Springs and Comal Springs. The regional flow in the Barton Springs Formation is from Onion Creek toward Barton Springs. In addition to the recharge, the Edwards Aquifer also receives some water from the Trinity Formation. The underflow from the Trinity Formation is estimated to be about 2% of the total recharge in the San Antonio segment and about 9% in the Barton Springs segment (Mace et al. 2000). In addition to the recharge, the regional flow is affected by anthropogenic pumping and discharges to the springs in the aquifer, which is discussed next.

The discharges from the Edwards Aquifer are due to springflows and withdrawals by humans. The springflows in the San Antonio segment, particularly in the Comal Springs and San Marcos Springs, are depicted in Figure 5.3. As can be seen, the springflows vary considerably and were lowest during the 1950s, when central Texas experienced severe and prolonged droughts. Well yields of greater than 1000 gal/min have been noted in the confined portions of the Edwards Aquifer, and

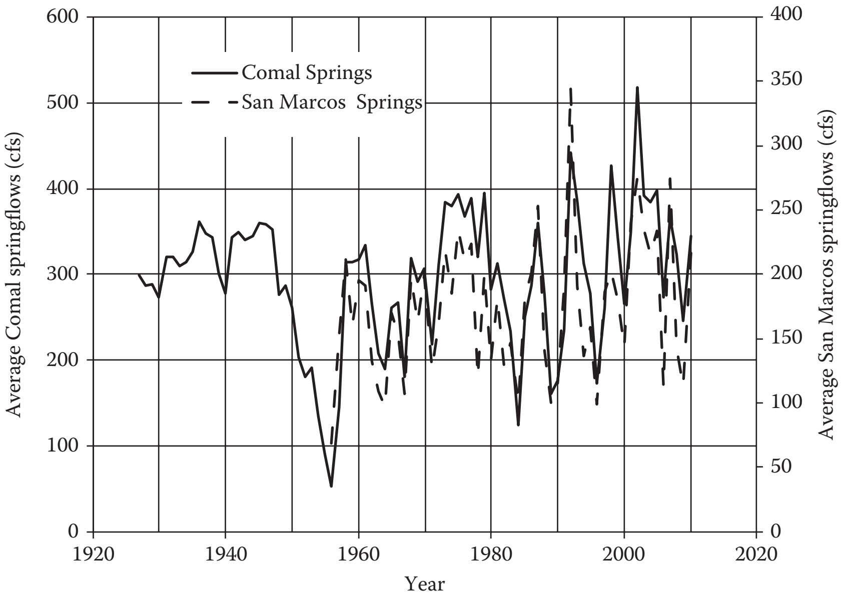


FIGURE 5.3 Annual average Edwards Aquifer San Antonio pool discharges into Comal Springs and San Marcos Springs. (Adapted from EAA. 2011. http://edwardsaquifer.org/display_policies_rules_s.php?pg=groundwater_management_plan. Accessed October 2011.)

yields of several hundred gallons can be obtained from the unconfined portions. More than 60% of the groundwater use in Uvalde County and more than 80% in Medina County are for irrigation purposes. Groundwater withdrawals for municipal uses are another important source of discharge from the Edwards Aquifer. The withdrawals by the city of San Antonio are depicted in Figure 5.4 and are seen to steadily increase, as the population of Bexar County increased from nearly 293,000

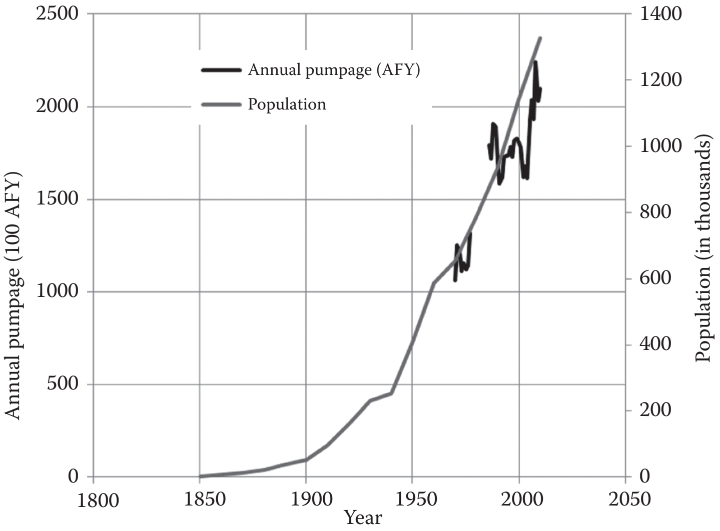


FIGURE 5.4 Population and annual groundwater withdrawals by the city of San Antonio. (Adapted from U.S. Census. United States Census Bureau quickfacts. 2010. http://www.census.gov/popfinder/. Accessed October 2011; EAA. 2011. http://edwardsaquifer.org/display_policies_rules_s.php?pg=groundwater_management_plan. Accessed October 2011.)

in 1939 to over 1.7 million in 2010. Municipal water withdrawals account for more than 85% of the total groundwater extractions in Bexar, Hays, Kinney, and Travis Counties, which are predominantly urban. The withdrawals in the San Antonio segment are concentrated around the city of San Antonio (Bexar County) and the city of Uvalde.

The increased groundwater withdrawals from the Edwards Aquifer have led to conflicts between municipal interests and rural and environmental groups. These conflicts have paved the way for creating a complex regulatory framework to manage the aquifer and to ensure that both the economic demands and the ecological needs are met in a sustainable manner. The conflicts between the municipal and environmental groups have also had a profound impact on the agricultural activities in the region, along with the conflicts between agricultural and environmental groups. The conflict over the Edwards Aquifer waters and the creation of the current aquifer management framework are discussed next.

5.4 REGULATORY FRAMEWORK FOR MANAGEMENT OF THE EDWARDS AQUIFER

Historically, the groundwater resources in Texas have been considered private property and the landmark "rule-of-capture" decision in the *Houston & Texas Central Railroad Co. v. East* by the Texas Supreme Court in 1904 has been the basis of the regulation (or lack thereof) of groundwater resources (Potter 2004). As per the "rule of capture," a property owner has the right to produce groundwater underneath his/her property as long as it is for beneficial use, even if it limits the ability of the neighbors to withdraw and use the water. This law has aptly been dubbed as the law of the largest pump because it has resulted in a tragedy of the commons situation and an inefficient use of groundwater resources. The recognition of the overexploitation of the aquifer resources under the rule of capture prompted the state of Texas to develop legislation that allowed for the creation of underground water or groundwater conservation districts (UGWCDs or GCDs). While the Edwards Underground Water District (EUWD) was created by the 56th Legislature of Texas in 1959 to protect and preserve the Edwards Aquifer, it did not have significant regulatory authority. In 1989, Uvalde and Medina Counties pulled out of the EUWD because of disagreements over pumping limits and established single county underground water districts. In 1991, the Sierra Club joined the Guadalupe-Blanco River Authority (GBRA) and others to file a suit in the U.S. District Court alleging that the Secretary of the Interior and the U.S. Fish and Wildlife Service (USFWS) failed to protect the endangered species dependent on the aquifer. In February 1993, Judge Lucius Bunton ruled in favor of the plaintiffs, determining that unabated pumping will lead to takings (of water rights) from the endangered and threatened species.

The Edwards Aquifer Authority (EAA) was created by the 73rd Legislature in response to the judge's ruling with the regulatory authority to regulate groundwater withdrawals in the aquifer such that sufficient environmental flows are maintained in the Comal Springs and the San Marcos Springs. The permitted withdrawal (excluding exempt use and those by federal agencies) from the aquifer within the jurisdictional boundaries of the Edwards Aquifer is capped at 572,000 AFY (EAA 2011). As the Edwards Aquifer responds quickly to pumping and drought events, the EAA uses a critical period management plan (CPMP) to reduce withdrawals from the aquifer based on the observed springflows and water levels in the aquifer. The flows in the San Marcos Springs and the Comal Springs as well as the water levels in the J-17 index well in Bexar County are used to regulate the San Antonio pool of the Edwards Aquifer. By the same token, the J-27 index well in Uvalde County is used as an indicator to specify critical management periods in the Uvalde pool of the aquifer. As can be seen from Table 5.1, as much as a 40% reduction from the originally permitted amount may become necessary under prolonged drought situations. In a similar fashion, the Barton Springs Edwards Aquifer Conservation District (BSEACD) uses the Barton Springs discharge and water levels in the Lovelady index well to regulate pumping in the aquifer.

TABLE 5.1
Pumping Reduction Policies of the Edwards Aquifer Authority for the San Antonio Pool

	Critical Period			
Trigger	**Stage I**	**Stage II**	**Stage III**	**Stage IV**
Index well J-17 (MSL)	<660	<650	<640	<639
San Marcos springflow (cfs)	<96	<80	N/A	N/A
Comal springflow (cfs)	<225	<200	<150	<100
Withdrawal reduction	20%	30%	35%	40%

Source: EAA. Edwards Aquifer Authority. 2011. http://edwardsaquifer.org/display_policies_rules_s.php?pg=groundwater_management_plan. Accessed October 2011.

5.5 AGRICULTURE IN THE EDWARDS AQUIFER AREA

Historically, agriculture and ranching have been an important water-use group in the Edwards Aquifer region. Irrigated farming has been used to grow crops, such as cotton, corn, sorghum, nuts, and vegetables. However, as can be seen from Table 5.2, the majority of the farmland is used as pastures, and cattle rearing and ranching activities are predominant in the area. Generally speaking, agricultural activities are more prominent in the western sections of the study area and generally decrease in the eastward direction because of the urban sprawl of the Austin–San Antonio metropolitan corridor and also because of poor quality water.

Water needs for agricultural practices have also been a source of controversy in the Edwards Aquifer region. Historically, the farming interests in the region have fought hard to retain the rule of

TABLE 5.2
Distribution of Farmland and Average Farm Owner Age in Edwards Aquifer Study Area

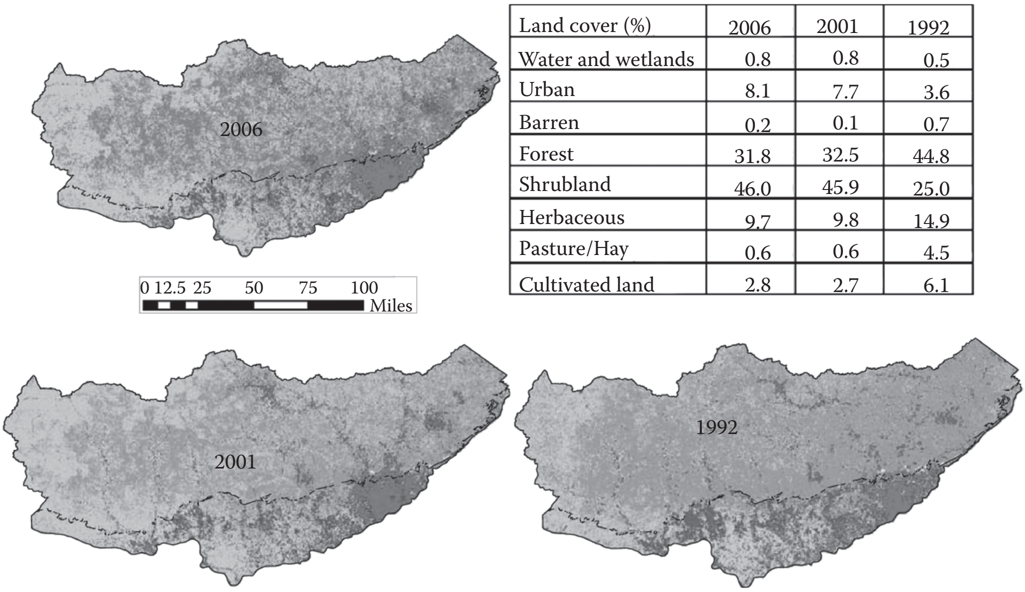
	Distribution of Farmland for Various Activities (%)				
County	**Pasture**	**Cropland**	**Other**	**Change in Total Farmland Since 2002 (%)**	**Average Farm Owner Age**
Bandera	76.43	6.5	17.07	–10.75	62
Bexar	61.75	29.44	8.81	–3.53	60.2
Comal	64.86	19.47	15.67	–5.48	59.8
Edwards	95.06	0.00	4.94	2.00	58.4
Hays	65.99	16.67	17.34	2.33	60
Kendall	77.68	9.95	12.37	–16.65	59.6
Kerr	82.67	6.56	10.77	4.65	60.9
Kinney	91.11	0.00	8.89	8.35	60.1
Medina	63.08	23.2	13.72	–2.04	59.2
Real	81.08	7.01	11.91	–7.31	62.7
Travis	57.42	28.9	13.68	–7.13	59.6
Uvalde	79.11	13.3	7.59	–12.82	60.4

Source: USDA. The agricultural census of 2007. 2011. http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_2_County_Level/Texas/index.asp. Accessed October 2011.

capture. In 1989, Uvalde County and Medina County pulled out of the original EUWD and formed single county districts over disputes arising from establishing production limits and drought management plans (Votteler 1998). Today, these districts continue to locally regulate the groundwater resources under the broader umbrella of the EAA. The region has also seen conflicts between agricultural and environmental groups, which have had an impact on the agricultural activities. In 1995, the Sierra Club sued the U.S. Department of Agriculture (USDA) under the Endangered Species Act, alleging that the USDA was allowing agricultural activities to harm the species in the aquifer. In 1996, in response to this lawsuit, the USDA was ordered to develop a species conservation plan. An investigation by Schaible et al. (1999), however, indicated that the USDA farm programs do not apparently play a substantial role in the total debate of sharing waters.

While the establishment of the EAA and the subsequent regulation of the Edwards Aquifer are viewed as a careful compromise between the environmental, urban, and agricultural interest groups, several provisions are considered particularly favorable for agricultural interests. In particular, there are provisions that require the EAA to treat agricultural water uses on a par with municipal and environmental needs. The agriculture share is guaranteed to be proportional to the historical share and the farmers are guaranteed a minimum of 2 AFY/acre of land used historically for farming. While the EAA allows for water transfers and leases between different water-user groups, transfers from agricultural permits are limited such that at least 1 AFY/acre must be retained for agricultural use. Agricultural users are only charged \$2.00/acre-feet of water, whereas municipal and industrial permit holders are currently charged \$39.00/acre-feet of water (EAA 2011). Furthermore, farmers who have planted crops prior to the implementation of the Stage I critical management plan (drought contingency measure) are allowed to continue irrigating to properly close out their crops (EAA 2011). These provisions and rules are intended to address the concerns related to the preservation of irrigated agriculture and the mitigation of economic and social consequences in areas where few profitable alternatives exist.

The land cover within the Edwards Aquifer region in the years 1992, 2001, and 2006 is schematically depicted in Figure 5.5. As can be seen, the urban area has more than doubled during the 1990s. The agricultural area has decreased from over 10% of the study area to about 3.5% over a



Land cover (%)	2006	2001	1992
Water and wetlands	0.8	0.8	0.5
Urban	8.1	7.7	3.6
Barren	0.2	0.1	0.7
Forest	31.8	32.5	44.8
Shrubland	46.0	45.9	25.0
Herbaceous	9.7	9.8	14.9
Pasture/Hay	0.6	0.6	4.5
Cultivated land	2.8	2.7	6.1

FIGURE 5.5 Land cover changes in the Edwards Aquifer area during 1992–1996. Darker regions represent urban areas, while the lighter regions represent agricultural and rangelands.

15-year period. The total area under farms during the years 2002 and 2007 was analyzed to evaluate whether special provisions aimed at preserving agricultural practices in the region were serving their intended purpose, using agricultural census data for these 2 years. The total acreage under agriculture increased in Kerr and Kendall Counties in the north and Uvalde and Edwards Counties in the west. However, the land under agriculture decreased in the remaining eight counties. The reduction in agricultural farmland was particularly significant in Hays and Travis Counties, which lie close to the Austin city limits, as well as in Real and Medina Counties, which are adjacent to the city of San Antonio. Overall, the region saw a loss of over 130,000 acres in the 5-year evaluation period between 2002 and 2007.

The estimated historical use of the Edwards Aquifer has been compiled by the U.S. Geological Survey (USGS) and the EAA. These data provide another indirect approach to evaluate the conflicts between urban and rural interests and temporal shifts between the two water-use groups. The water-use data presented in Figure 5.6 demonstrate how both agricultural and municipal demands continued to rise in the period between 1950 and 1980. In the last few decades, the municipal demand has clearly slowed down but continues to see a slow increase. On the other hand, the agricultural water use has seen a remarkable reduction, particularly after 1995 (i.e., after the creation of the EAA). The average agricultural water use during the period 1975–1995 was approximately 125,000 AFY; however, during the 1996–2007 period, the average agricultural use dropped to nearly 100,000 AFY. On the other hand, the municipal use averages have been 245,000 AFY (during 1975–1995) and 250,000 AFY (1996–2007). The drop in the agricultural water use along with the changes in the land cover clearly point toward diminished agricultural activities, and a vast majority of the agricultural land is now being used as pasture (USDA 2011).

The regulatory mandates of the EAA also include the establishment of groundwater rights and the development of instruments that facilitate water sales and leases. The transfer of water from agriculture to municipal uses is favored in the economic literature as it generally moves water from low-valued use to a higher-valued use and increases economic efficiency (e.g., Titenberg 2005). The theoretical investigation of McCarl et al. (1999) indicates that the emergence of a water market is likely under tight pumping regulations in the Edwards Aquifer region. In particular,

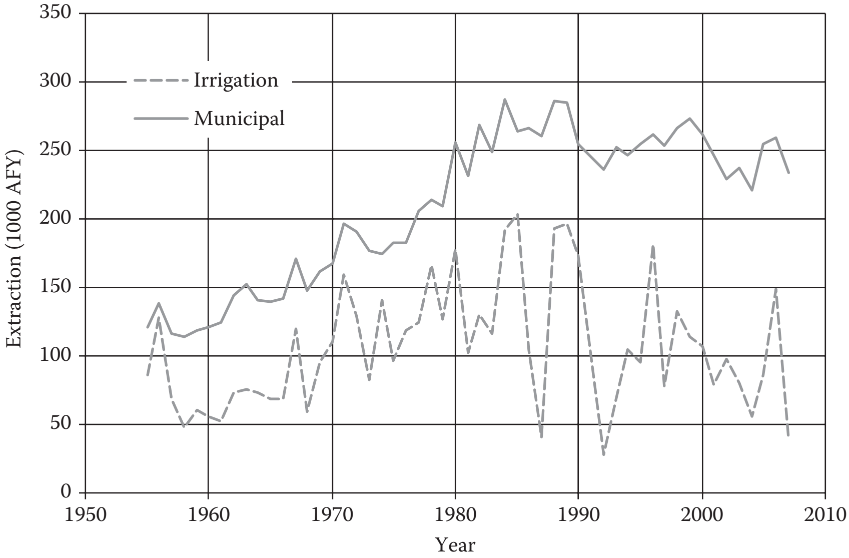


FIGURE 5.6 Historical agriculture and municipal pumping in the Edwards Aquifer area. (Adapted from EAA. 2011. http://edwardsaquifer.org/display_policies_rules_s.php?pg=groundwater_management_plan. Accessed October 2011.)

agricultural guarantees, such as proportional pumping and at least a 2 AFY/acre allocation, are seen to be necessary to preserve agricultural welfare, but also point toward the development of a viable water market where nonagricultural users can obtain agricultural water by making fair compensations. The empirical investigation by Kaiser and Phillips (1999) indicates that many farmers in the Edwards Aquifer region generally have expressed a willingness to engage in such transactions under a suitable compensatory framework. The reallocation of water between the agricultural and the municipal sectors partially explains the decrease in the agricultural activities and dry-year transfers from low-valued crops have been noted in the area (Keplinger and McCarl 2000). Anecdotal evidence indicates that social issues and local concerns could impose huge transaction costs on such transfers and, as such, this is not the only factor affecting the decreasing agricultural activities.

The shift from growing water-intensive crops, such as corn, to ranching-oriented operations (pasture) is an important factor that affects the reduction in agricultural water use. The EAA also requires that farmers exhibit at least 60% irrigation efficiency or implement a groundwater conservation management plan. This strategy has played a significant part in reducing groundwater use for irrigation, which, in turn, has been used to augment other needs (IEA 2002). According to one estimate, approximately 11% of conserved water has been transferred to municipal uses in Uvalde County (IEA 2002).

5.6 FUTURE OF AGRICULTURE IN THE EDWARDS AQUIFER REGION

The sustainability of the fast-paced urbanization of the San Antonio–Austin metropolitan corridor critically hinges on the availability of water resources. The State of Texas Water Plan indicates that the region could experience shortfalls in supplies by the year 2030 (TWDB 2007). The predictions of the general circulation models (GCM) indicate that the problematic climate of south Texas will be further exacerbated with an increase in the annual temperature of about 4°C by the turn of the century (IPCC 2007). While an ensemble of GCMs predict no significant changes in the annual precipitation, the region is projected to experience prolonged droughts and greater intensity storms, which result in greater runoff and limited storage opportunities (Norwine et al. 2007; IPCC 2007). Predictive modeling appears to indicate that climate change is likely to have a significant impact on the soil water availability in the region (Uddameri and Parvathinathan 2007) and, as such, it will increase the need for irrigation. It is projected that the economic losses to the region due to climate change could be almost $10.0 million/year (Chen 2001).

Water use for agricultural and municipal uses is strongly correlated in the Edwards Aquifer region, as it appears from Table 5.3. A county-by-county assessment of the groundwater production data indicates that the competition between urban and agricultural uses has increased over the last few years, both in the urban and rural areas. This competition becomes more intense during the periods of drought as the total amount of available water is insufficient to meet all demands and some sacrifices have to be made. An increasing population in the urban areas will increase the purchasing power of the municipalities to obtain water from irrigators, and farmers may find it profitable to sell their water rights to municipalities rather than engage in agricultural activities. The dry-year water-use reduction incentives are shown to be a major policy instrument to reduce conflicts between urban, rural, and environmental interests (Schaible et al. 1999; IEA 2002). Crop substitution, conversion to dryland farming, and the use of drought-tolerant varieties are likely to increase in the future.

The sustainability of agriculture in the Edwards Aquifer region greatly hinges on the ability of the urban areas to find alternative supplies of water. Clearly, a reduction in the uptake of water by one user group benefits the other user groups. The city of San Antonio has in place a strong municipal water conservation program. The city has a pricing structure that explicitly funds a conservation program and has a water consumption rate goal of 110–133 gpcd, which is one of the best in the

TABLE 5.3
Correlation between Competing Groundwater Uses in the Edwards Aquifer Area

	Irrigation	Municipal	Livestock	Industrial	Spring
Irrigation	1.00				
Municipal	0.49	1.00			
Livestock	0.24	–0.02	1.00		
Industrial	–0.14	0.23	–0.63	1.00	
Springs	–0.44	0.22	–0.09	0.09	1.00

Source: Based on data from EAA. Edwards Aquifer Authority. 2011. http://edwardsaquifer.org/display_policies_rules_s.php?pg=groundwater_management_plan. Accessed October 2011.

nation (NWF 2010). The city has also invested in the development of the Twin Oaks Aquifer storage and recovery (ASR) system in southern Bexar County to store available surplus water from the Edwards Aquifer in the Carrizo Aquifer to meet the city's demands during times of low supplies. The utility of this facility in augmenting San Antonio's water demands during low-flow periods was demonstrated during the droughts experienced in 2006 and 2009. In addition, San Antonio is actively evaluating and pursuing other demand management and supply augmentation strategies, such as the use of treated wastewater for watering golf courses, ocean water desalination, and recharge enhancement of the Edwards Aquifer using check dams. The city's goal of reducing its reliance on the Edwards Aquifer not only helps environmental interests, but also has clear benefits for the agricultural sector in the region. However, certain long-term strategies being pursued by the San Antonio Water System (SAWS), such as the leasing of water in the neighboring Carrizo Aquifer as well as the LCRA/SAWS project in the Gulf Coast Aquifer, have the potential of removing water from the agricultural sector albeit not in the Edwards Aquifer region. Thus, the competition and contention in the Edwards Aquifer region can have negative spillover effects on agriculture in the neighboring areas as well.

On a much broader scale, there is a diminishing trend in the number of students pursuing agricultural studies in the United States (Harlin and Weeks 2001). Furthermore, younger farmers are noted to be more economically diversified and are more apt to simultaneously pursue both agricultural and nonagricultural interests (Caldwell 2011). The data pertaining to the average farmer age and changes in agricultural land are summarized in Table 5.2 and appear to point toward that trend in the study area as well. A detailed evaluation of the U.S. Agricultural Census indicates that the peri-urban counties in the study area have a greater percentage of younger farmers and it is very likely that they will be more inclined to curtail farming than older farmers who may not have other skill sets to diversify. Thus, it is critical that the socioeconomic importance of agriculture to the region be recognized and imparted to younger audiences in the region if agricultural activities are to be sustained at present-day levels.

5.7 CONCLUSION

The overall goal of this study is to undertake a historical assessment of water conflicts in the Edwards Aquifer region in an effort to understand how the evolving groundwater management policies and actions by competing municipal and environmental groups have impacted the agricultural activities in the region. The competing demands on scarce water resources arising from a growing population and a strong interest in protecting endangered species unique to the Edwards Aquifer place constraints on sustaining agriculture in the region. The current regulatory framework in place, however, provides several incentives, such as equal protection of agricultural water rights, subsidized water costs, and provisions to continue irrigation for crop closeouts during droughts. Nonetheless, there has been a net reduction of about 130,000 acres of total farmland between the years 2002 and 2007. These farmland losses are more pronounced in the periurban areas surrounding Austin and San Antonio. The current regulatory framework allows for partial water transfers between agricultural and nonagricultural uses, and there is a general willingness noted among farmers to market water under sufficient economic gains. It is likely that the projected drier, warmer climate for the region may increase the transfer of water from the agriculture to the nonagricultural sector. The city of San Antonio has an aggressive plan to minimize its reliance on the Edwards Aquifer, which will eventually benefit agricultural interests in the region, but may do so at the cost of curtailing agriculture in the surrounding areas of the state. For long-term agricultural sustainability, it is important that the critical role of agriculture in shaping the region's economy is highlighted and is used to encourage younger minds to pursue agriculture-oriented education.

ABBREVIATIONS

EAA	Edwards Aquifer Authority
EUWD	Edwards Underground Water District
FESA	Federal Endangered Species Act
GBRA	Guadalupe-Blanco River Authority
GCDs, UGWCDs	Groundwater conservation districts
GCM	General circulation models
SAWS	San Antonio Water System

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6 Sustaining Groundwater Use in South Asia

Meharban Singh Kahlon, Rattan Lal, and Pritpal Singh Lubana

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6.1 INTRODUCTION

Sustainable groundwater (GW) management is important to revitalize the green revolution (GR) in South Asia (SA). Together, the SA nations have over 2800 km^3 or billion cubic meters (BCM) of renewable freshwater resources (Gleick 1998). The GW overdraft and unsound management strategies now threaten the sustainability of the GR in the SA region. India is the largest GW user in the world. The annual replenishable GW resources of India are 433 BCM compared with the net annual GW availability of 399 BCM and the overall GW development of 58%. The renewable water resources of India are about 4% of the global availability (IWRS 1998). More than 60% of India's irrigated agriculture depends on GW, which was only 29% in 1950–1951 (WPB 2002). Similarly, in Pakistan, Bangladesh, and Nepal, GW is used in over 75% of the irrigated areas. At present, GW irrigation has surpassed surface (canal) irrigation as the primary source of food production and income generation in many countries of SA. GW depletion is a big problem in India and Pakistan (Postel 1999), whereas GW pollution is a major issue in Bangladesh and Nepal (Khan 1994). Due to the excessive mining of GW, the water table (WT) has been depleting by as much as 30 cm/year in northwestern India. GW pumping with electricity and diesel pump sets also accounts for an estimated 16–25 Tg of carbon (C) emission in the atmosphere. Likewise, there is also the problem of water logging and rises in the water table in some parts of India and Pakistan caused by seepage from water sources (e.g., unlined canals), excessive irrigation by flooding, and lack of drainage to safely remove the excess water. The key question for policy makers, planners, and researchers is how to exploit the resource without exhausting its supply and without damaging the environment. This chapter outlines the concepts and approaches for sustainable GW use and describes the factors affecting its availability without adversely affecting the hydrogeological balance, crop production, and the environment. This chapter also discusses a range of techniques for the sustainable management of GW, including the need for rainwater harvesting (RWH) and artificial recharge, and it outlines some relevant policy interventions at local and regional levels.

GW is a primary source of fresh water in many parts of the world and it constitutes about 89% of the total freshwater resources of the planet (Gleick 1993; Shah et al. 2007; Menon 2007). The growth of GW resources in selected SA countries is closely linked to the dependence on extensive irrigation in SA (Figure 6.1; Shah and Mukherjee 2001; Roy and Shah 2002; Shah 2007; Scott and Sharma 2009). GW irrigation has played a significant role, along with surface (canal) irrigation, in creating the GR and enhancing the livelihoods of hundreds of millions of people. In India, food production increased from 50.8 million Mg (M Mg) in 1950–1951 to 215.0 M Mg in 2005–2006, partly because of the increase in the irrigated area under surface and GW irrigation (Figure 6.2). Indian agriculture primarily depends on

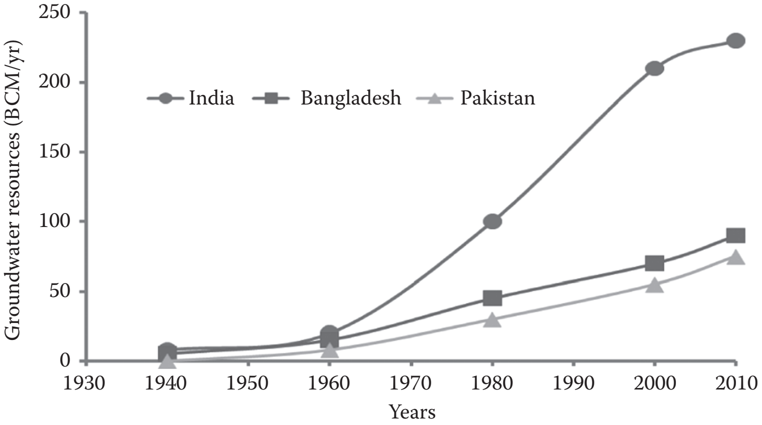

FIGURE 6.1 The growth of groundwater in South Asia. (Modified from Shah, T., *The Agricultural Groundwater Revolution: Opportunities and Threat to Development*, CABI Publishing, Wallingford, UK, 2007.)

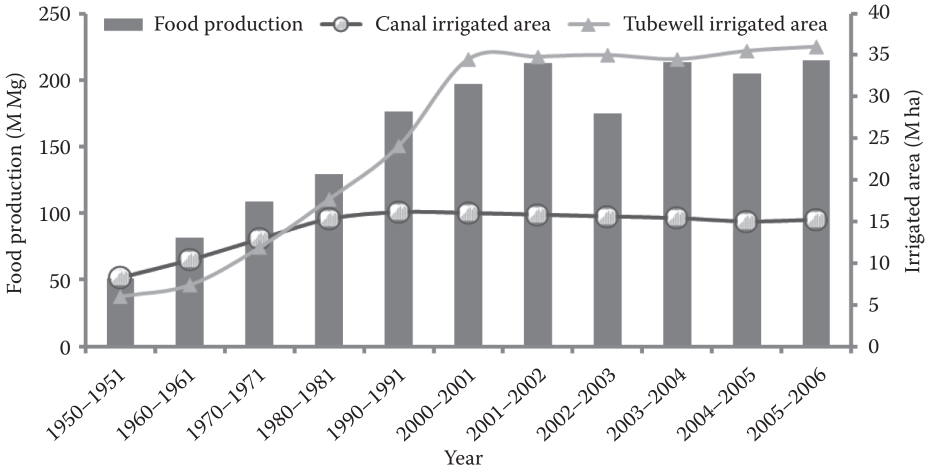

FIGURE 6.2 The increase in food production with an increase in the irrigation facilities in India. (Modified from GOI, Ministry of Agriculture, as given in Vaidyanathan, 1999: 61; Central Water Commission, Water and Related Statistics 1994, p. 81, 1995/96: Fertilizer Association of India, Fertilizer Statistics 1998/99; Planning Commission, GOI, Eleventh 5 Year Plan, Vol. III, 2008.)

GW obtained by large numbers of pump sets (Shah 2009a). Between 1970 and 1994, the area under GW irrigation increased by 105%, compared with an increase of only 28% of the area under surface water irrigation in India (Shah 2002). The number of mechanized wells and tube wells in India increased from less than 1 million in 1960 to 19 million in 2000, registering the maximum pump sets in the world. In Pakistan's Punjab, the number of wells and/or tube wells increased from a few thousand in 1960 to 0.5 million in 2000. In Bangladesh, which hardly had any GW irrigation until 1960, the area under irrigated cropland by tube wells increased from 4% in 1972 to 70% in 1999 (Mainuddin 2002). In India, Bangladesh, and Nepal, the modal pump size is 6.5 hp and the average duration of operation is 400–500 h/year (Shah 1993). GW depletion is primarily caused by sustained pumping throughout SA. The mean GW level in the region is decreasing at a rate of 4.0 ± 1.0 cm/year (an equivalent water height of 17.7 ± 4.5 BCM/year), as observed over the Indian states of Rajasthan, Punjab, and Haryana (including Delhi) (Rodell et al. 2009). This rate of GW depletion is equivalent to a net loss of 109 BCM of water, which is double the capacity of India's largest surface water reservoir. In the current scenario, water has become the single most important constraint to increasing food production (Seckler et al. 1998a,b; Dennehy et al. 2002; Chatterjee and Purchit 2009). In humid areas, rainfall distribution is such that there is no need for additional water application. In arid and semiarid areas, where crop failures occur due to water deficiency, farmers resort to supplemental irrigation. Because the SA region has a predominantly arid and semiarid climate, the rainfall is not adequate to recharge the GW, and excessive mining of GW for irrigation causes WT depletion. Only 58% of India's GW is recharged every year (www.indusenviro.com Regulatory News Update No. 39 August, 2009).

In the Indian subcontinent, GW use increased from 10–20 BCM in 1950 to 240–260 BCM in 2000 (Shah 2005). Farming has turned into a race to keep food production ahead of the population, which unfortunately requires the extraction of more and more natural resources. High-yielding varieties (HYV) in combination with fertilizer and pesticides produce two to three times more than the traditional varieties (Lappe et al. 1998), but they also require three times more water. In terms of water use, therefore, they are less than half as productive (Shiva 1991). Rice (*Oryza sativa* L.), which is the second dominant crop of the SA region, further adds to the decline in GW in the region because it demands six times more water than wheat (*Triticum aestivum* L). Another reason for the depletion of GW is the increasing demand from the domestic, industrial, and hydroelectric sectors. In Pakistan's Punjab, the WT is dropping at 3–9 m/year. The growing shortages of GW are leading

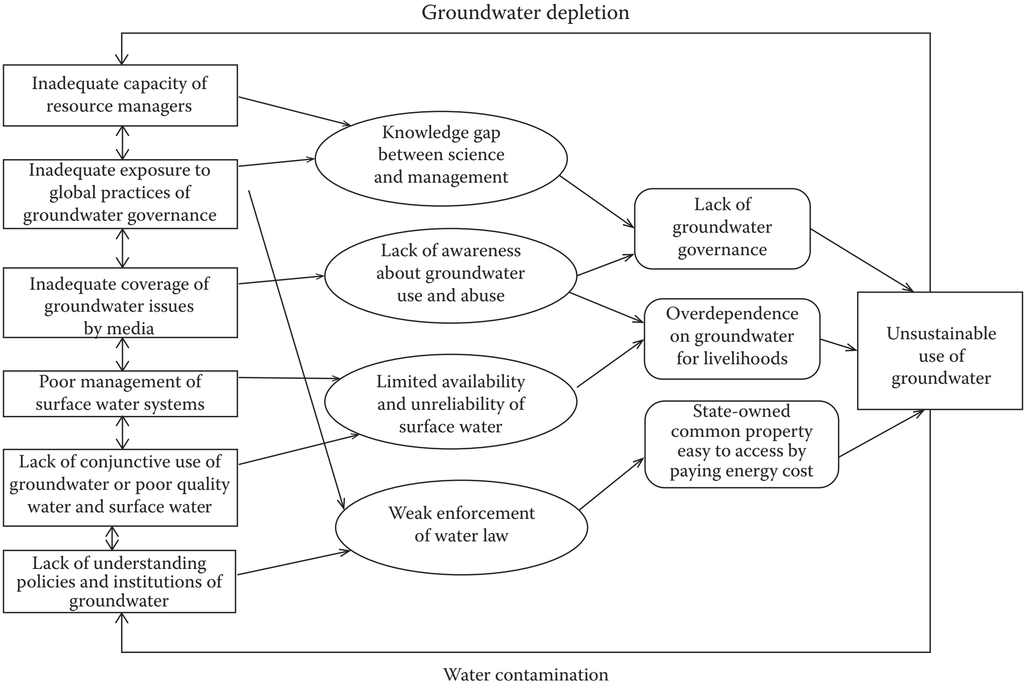
Groundwater depletion
Inadequate capacity of resource managers
Inadequate exposure to global practices of groundwater governance
Inadequate coverage of groundwater issues by media
Poor management of surface water systems
Lack of conjunctive use of groundwater or poor quality water and surface water
Lack of understanding policies and institutions of groundwater
Knowledge gap between science and management
Lack of awareness about groundwater use and abuse
Limited availability and unreliability of surface water
Weak enforcement of water law
Lack of groundwater governance
Overdependence on groundwater for livelihoods
State-owned common property easy to access by paying energy cost
Unsustainable use of groundwater
Water contamination

FIGURE 6.3 The factors responsible for the unsustainable use of groundwater. (Adapted from Challenge Program on Water and Food [CPWF] project report, IWMI, No. 42, 2009.)

to social and ethnic conflicts. Some of the negative effects of GW depletion include the drying up of wells, the reduction of water in streams and lakes, the deterioration of the water quality, increased pumping and electricity costs, and land subsidence.

There are several reasons for overdrafting (Figure 6.3), but the electrical supply and pricing are the primary reasons for GW irrigation pumping, particularly in India (Scott and Shah 2004). Freshwater withdrawal for various uses is the highest at ~380 BCM/year in India, 155 BCM in Pakistan, 22 BCM in Bangladesh, and 6 BCM in Sri Lanka (Subramanian 2000). By 2040, India as a whole will come under the group of water-stressed countries if measures are not taken soon to ensure sustainable GW usage. It will cause a reduction in agricultural output and shortages of potable water, leading to extensive socioeconomic stresses. Khair et al. (2010) suggested that resource management should be based on information gathering and resource planning by establishing appropriate systems for resource monitoring on a regular basis; demand side management through the registration of users through permits and a licensing system; appropriate laws and a regulatory mechanism; a pricing system for efficient water use; the promotion of conjunctive water use; supply side management through RWH and surface water use for increasing recharge; and improving water conservation and undertaking GW management at river basin level. Molden (2007) suggested that water can be efficiently managed by changing the way we think about water and agriculture, by improving access to agricultural water and its use, by managing agriculture to enhance the ecosystem service, and by increasing the productivity of water and upgrading the rainfed systems.

6.2 SIGNIFICANCE OF GW

Water is essential for all living beings—plants, animals, and people. GW is fresh water retained in the pores of soil and rocks. It is also the water that flows within aquifers below the WT. It is a unique resource, widely available, providing security against droughts and yet it is closely linked to the surface water resources and the hydrological cycle. Its reliable supply, uniform quality, temperature, relative turbidity, low pollution concentration, minimal evaporation losses, and low cost of development are the critical attributes that make GW a precious resource. GW is a finite but renewable resource that is intrinsically linked to surface water and other natural resources (Custodio et al. 2004). It is generally a more reliable freshwater resource than surface water and can be readily developed to meet human needs and agricultural demands.

6.2.1 ECONOMIC PERSPECTIVES OF GW

During the 1980s, the contribution of GW irrigation to India's gross domestic product (GDP) was around 10% (Daines and Pawar 1987). Extrapolating to the present, the size of the GW irrigation economy of India would be \$50–\$55 billion during the 2000s. India, Pakistan, and Bangladesh have active markets in pump irrigation services in which tubewell owners sell GW irrigation to their neighbors at a price that exceeds their marginal cost of pumping. Giordano and Villholth (2007) reported that this price offers a market valuation of GW use in irrigation. In India, for instance, a large number of farmers paid their neighboring borewell owners \$0.04 per m^3 for GW irrigation in 2003; applying this price to the annual GW use of 200 BCM yields \$8 billion as the annual economic value of the GW used in Indian agriculture (Table 6.1). For the Indian subcontinent as a whole, the corresponding estimate is around \$10 billion (Shah 2007). In many parts of water-scarce India, water buyers commonly enter into pump irrigation contracts, offering as much as one-third of their crop share to the irrigation service provider. In water-abundant areas, by contrast,

TABLE 6.1
Groundwater Resources, Economy, and Contribution to Irrigation in South Asia

	India	Pakistan	Bangladesh	Nepal
Annual GW use (BCM)[a]	189–204	54.5	31.2	0.37
Percentage withdrawal to renewable GW[b]	45.3	109.1	52.4	—
Percent of national share of global withdrawals[b]	28.9	9.1	1.7	—
Number of wells (million)[a]	21.0	0.5	0.8	0.06
Average output/well (m^3/h)[a]	25–27	100	30	30
Average hours of operation/(well year)[a]	360	1,090	1,300	205
Percent of population dependent on GW	55–60	60–65	64	—
Percent of GW as part of water resource used	53	34	69	12
Total irrigation water use (million m^3/year)	460,000	150,600	12,600	28,700
Price of pumping irrigation (\$/h)[a]	1–1.1	2	1.5	1.5
Value of GW used per year in billion dollars[a]	7.6–8.3	1.1	1.6	0.02

[a] Shah, T., *The Agricultural Groundwater Revolution: Opportunities and Threat to Development*, CABI Publishing, Wallingford, UK, 2007.

[b] FAO, AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm; 40, 41).

TABLE 6.2
Contribution of Surface Water (SW) and Groundwater (GW) to Irrigation and Total Agricultural Output of India

Year/Indicator (At 1990 Dollar/Rupee Exchange Rate)	1970–1973	1990–1993	Change (%)
Avg. agri. productivity ($/ha)	261.4	470.3	79.9
Contribution of SW ($/ha)	41.3	62.6	51.6
Contribution of GW ($/ha)	13.3	74	456.4
Contribution of SW (million $)	4,680	7,005	49.7
Contribution of GW (million $)	1,320	7,297	452.8
Contribution of SW as a percentage of the total agricultural output	15.5	13.9	−1.6% points
Contribution of GW as a percentage of the total agricultural output	4.4	14.5	+10.1% points
Total agricultural output/year (million $)	28,282	49,891	76.4

Source: DebRoy, A. and Shah, T., *Intensive Use of Groundwater: Challenges and Opportunities*, Swets & Zetlinger, The Netherlands, 2003.

the purchased pump irrigation cost generally amounts to 15%–18% of the gross value of the output it supports (Giordano and Villholth 2007).

6.2.2 Land Productivity and Food and Social Security

The contribution of the GW irrigated area to the total agricultural output of India is ten times more than that of the surface irrigated area (Table 6.2). Evidence in India suggests that a crop yield per cubic meter of water applied on GW irrigated farms tends to be three times higher than that applied on surface water irrigated farms (Dhawan 1989). Land productivity is also observed to be more under tubewell irrigation than under surface (canal) irrigation (Table 6.3). When irrigation is applied through GW, it adds a lot of nutrients, particularly sulfur (S) and

TABLE 6.3
Land Productivity per Net Irrigated Hectare by Sources of Irrigation (Mg/ha in Food Grains Energy Equivalent Units)

State	Wells	Canal Irrigation	Tanks
Andhra Pradesh	5.7 (67.6)[a]	3.4	2.0
Tamil Nadu	6.5 (150)[a]	2.6	2.3
Punjab	5.5 (71.9)[a]	3.2	—
Haryana	5.7 (137.5)[a]	2.4	—
Madhya Pradesh	2.8 (40)[a]	2.0	1.5
Karnataka	4.2 (20)[a]	3.5	2.3

Source: The World Bank, *Groundwater Regulation and Management in India*, The World Bank, vol II, p.7, Washington, DC and Allied Publishers, New Delhi, India, 1991.

[a] Figures in parentheses in the second column are the percentage by which productivity in well-irrigated areas is higher than in canal irrigated areas.

TABLE 6.4
Growth of Wells (Thousands) in India

Year	Dug Wells	Private and Public Tube Wells	Total
1951	3,860	5	3,865
1980	7,786	2,165	9,951
1985	8,742	3,405	12,147
1990	9,407	4,817	14,224
1992	10,120	5,446	15,566
1997	10,501	6,833	17,334

Source: Planning Commission report, India 2007: Groundwater Management and Ownership.

potassium (K), to enrich the soil. Since the 1990s, food production has hardly been affected by a single drought (Sharma and Mehta 2002), despite a string of two to three drought years, because of GW availability during a stress or drought period. Thus, GW development has been a major factor in India's food security and has been a key determinant in transforming Bangladesh from an endemic rice importer into a net rice exporter (Palmer-Jones 1999). Wells have also created greater spatial, social, ethnical, and interpersonal equity in the access to irrigation, especially when compared with large public canal irrigation systems that have created islands of agrarian prosperity (Giordano and Villholth 2007). Whereas the amount of GW contributing to agriculture is less than that of surface water on the global scale, its unique advantages (i.e., reliability, accessibility, on-demand availability, less capital investment, and high productivity) outweigh those of access to surface water. In India, Pakistan, Bangladesh, and Nepal, the GW contribution to the irrigated areas exceeds that of surface water (DebRoy and Shah 2003; Shah et al. 2006). It is also observed that in northwestern India, despite massive investments in canal irrigation, the bulk of the irrigation is delivered by wells and tube wells. From 1950 onward, there has been a continuous increase in the number of wells dug and the number of private and public tube wells (Table 6.4). No wonder, then, that in developing regions of SA, GW development has become the central element of livelihood creation programs for the poor (Kahnert and Levine 1993; Shah 1993; Rosegrant 1997; Calow et al. 1997).

6.3 GW RESOURCES IN SOUTH ASIAN REGION

6.3.1 Water Resources in India

The GW resources of India constitute one of its vital assets. Kumar (2006) assessed that the total annual replenishable GW resources of India are 432 BCM (contributed by rainfall and other sources in the proportion of 67% and 33%, respectively). Other sources include canal seepage, return flow from irrigation, seepage from water bodies, and artificial recharge due to water conservation structures. Together, the annual utilizable surface water and GW are estimated at 690 BCM (Kumar et al. 2005). India's GW resources would be about 300 M ha-m or about 10 times the annual precipitation (Shah 2005). India uses an estimated 230 BCM of GW every year, of which 212 BCM (92%) is used for irrigation purposes and 18 BCM (8%) is used for domestic and industrial purposes (Chatterjee and Purchit 2009). According to the World Bank's report, GW supports >80% of the rural and urban water supplies in India (www.waterworld.com/./waterworld/world./2010//Groundwater-supplies-depleting-at-alarming-rate-in-India.html). The southwest monsoon, the most prevalent contributor of rainfall in India, recharges about 73% of the country's annual replenishable GW during the summer. The irrigation potential was only 22.6 M ha in 1950–1951, but it has now reached about 100 Mha. The projections for the future population and food requirements of the country indicate that the population of India may stabilize at around 1.6–1.7 billion by 2050 AD, which would require about 450 M Mg of food grains annually at the desired level of food consumption. It is necessary to equip irrigation on at least 130 Mha for food crops alone and on 160 Mha for all crops to meet the demands of the country in 2050 AD and ensure food security.

In India, as much as 195 BCM of water is available out of a total annual precipitation of about 4000 BCM. This water is harnessed as both surface water and GW. Surface utilization is mainly through dams constructed across rivers served by larger catchments and tanks served by smaller catchments. The GW is utilized mainly through both open wells and tube wells. The canal irrigated area has increased from 8.3 to 18 Mha during 1950–1951 and 1999–2000 (Table 6.5). Likewise, the well irrigated area has increased from 6 to 34 Mha during the 50 years that ended in 2010. During the period from 1950 to 1999, the area under irrigation with tanks decreased from 3.6 to 2.7 Mha. Tanks are mostly concentrated in regions where other sources of irrigation are either less or are completely absent. The annual potential GW recharge augmentation from the canal irrigation system is about 89.5 BCM (Kumar et al. 2005; CWP 2005). The available GW resource for irrigation is 360 BCM, of which the utilizable quantity is 325 BCM (90%). Precipitation and snowmelts are the only sources of fresh water that are stored in aboveground reservoirs or in GW aquifers below the surface. The total average annual flow per year for Indian rivers is estimated at 1953 BCM (Rama Krishna and Shiva Kumar 2008).

6.3.2 GW DEVELOPMENT IN PAKISTAN

Pakistan has a long history of using GW for irrigated agriculture. Until the 1960s, GW extraction was done by means of open wells with a rope and bucket, Persian wheels, karezes (a form of subterranean aqueduct), reciprocating pumps, and hand pumps. Large-scale extraction and use of GW for irrigated agriculture in Pakistan started during the 1960s with the launch of Salinity Control and Reclamation Projects (SCARPs). Under this program, 16,700 tube wells (supplying an area of 2.6 Mha) with an average discharge of 0.09 m^3/sec were installed to lower the WT, to create favorable crop growth conditions in the root zone, and to reduce the risk of soil salinization (Bhutta and Smedema 2007). The pumped GW was discharged into the existing public canal system to increase the irrigation supplies (Qureshi et al. 2008). The demonstration of SCARP tube wells was followed by an explosive development of private tube wells with an average discharge of 0.03 m^3/sec. The provision of subsidized electricity by the government and the introduction of locally made diesel engines provided an impetus for a dramatic increase in the number of private tube wells. Currently, about 0.8 million small capacity private tube wells are operational in Pakistan, of which more than 90% are used for agriculture (Qureshi et al. 2008). The geographic distribution of electric and diesel irrigation pumps for Pakistan and other SA countries is presented in Table. 6.6. Investments in the installation of private tube wells are of the order of Rs. 25 billion (US$400 million), whereas the

TABLE 6.5
Areas and Percentage Shares of Different Irrigation Sources in India

Sources of Irrigation	1950–1951 Area (Mha)	Percentage	1999–2000 Area (Mha)	Percentage
Canals	8.3	40	18	31.5
Wells and tube wells	6	29	33.6	58.7
Tanks	3.6	17	2.7	4.7
Other sources	3	14	2.9	5.1
Total	20.9	100	57.2	100

Source: Central Statistical Organization (CSO), Statistical Abstract, India, 2002.

TABLE 6.6
Geographic Distribution of Electric and Diesel Irrigation Pumps (%) in South Asia

Country	Diesel (%)	Electric (%)
Pakistan[a]	89.6	10.4
Bangladesh[b]	96.7	3.3
Eastern India[c]	84.0	16.0
Western India[c]	19.4	80.6

[a] Pakistan Agricultural Machinery Census 2004.

[b] Bangladesh: Mandal, 2006.

[c] Third Minor Irrigation Census 2000–2001.

annual benefits in the form of agricultural production are about Rs. 150 billion (US$2.5 billion) (Shah et al. 2003a). GW is currently providing more than 50% of the total crop water requirements with the flexibility of its availability as and when it is needed (Shah 2007). Punjab Province has taken the lead in the development of private tube wells (PWP 2001; GOP 2000). As a result, GW extraction increased from 9 to 45 BCM between 1965 and 2002 (Bhutta 2002; World Bank 2007).

6.3.3 SURFACE AND GW RESOURCES OF BANGLADESH

Bangladesh is endowed with plenty of surface water and GW resources. The average annual internal renewable water resources of Bangladesh are 105 BCM (WRI 2000). Bangladesh is located within the flood plains of three great rivers: the Ganges, Brahmaputra, and Meghna. The combined discharge of the three main rivers is among the highest in the world. Peak discharges are of the order of 1×10^{-4}, 7×10^{-5}, and 1.8×10^{-4} BCM/sec for Brahmaputra, Ganges, and Meghna, respectively. On average, almost 1106 BCM of water crosses the borders of Bangladesh annually, of which 85% crosses between June and October. About 54% (599 BCM) is contributed by the Brahmaputra, 31% (344 BCM) by the Ganges, and nearly 15% (163 BCM) by the tributaries of the Meghna and other minor rivers (www.fao.org/nr/water/aquastat/.../bangladesh/index.stm).

The availability of GW resources in Bangladesh is determined by the properties of the aquifers and the volume of annual recharge. The key factors that determine GW availability include the capacity of the country's aquifers to store water and its characteristics, which govern economic withdrawal of GW for irrigation, domestic, and industrial needs. The sources of recharge are rainfall, flooding, and stream flow in rivers. The quaternary alluvium of Bangladesh constitutes a huge aquifer with reasonably good transmission and storage properties. Heavy rainfall and inundation during the monsoon season help the aquifers to be substantially recharged annually. The total internal renewable water resources of the country are estimated at 105 BCM, with a negligible overlap (the volume of water resources common to both surface and groundwater). This includes 84 BCM of surface water produced internally as stream flows from rainfall and 21 BCM of GW resources produced within the country. In 2008, the total water withdrawal was estimated at about 35.9 BCM of which about 31.5 BCM (88%) was used for agriculture, 3.6 BCM (10%) for municipalities, and 0.8 BCM (2%) for industries. Approximately 28.5 BCM, or 79% of the total water withdrawal, comes from GW and 7.4 BCM, or 21%, from surface water. Arsenic (As) contamination in Bangladesh reached a drastic level during the last decade due to the overexploitation of GW and inefficient water resources management (Safiuddin and Karim 2003).

6.3.4 GW RESOURCES IN NEPAL

Nepal is a landlocked SA country. The average annual rainfall in the capital city Kathmandu is about 1300 mm (Jacobson 1996). Most of the rainfall occurs during the summer monsoon months

(June–September). These rains can cause severe flooding, especially in the Terai plains. GW is abundant in the aquifers of the Terai and Kathmandu valleys. About 50% of the water used in the city of Kathmandu is derived from GW (BGS 2001). GW availability is more limited in the populated hill regions because of the lower permeability of the indurated and crystalline rock types. Despite abundant rainfall, agricultural development is restricted by the limited development of irrigation. In the Kathmandu valley (area of 0.05 Mha), GW is extracted from two main aquifers within the thick alluvial sediment sequence. A shallow unconfined aquifer occurs at around 0–10 m depth and a deep confined aquifer occurs at around 310–370 m (Khadka 1993). The exploitation of these aquifers, especially the shallow aquifer, has increased rapidly in recent years as a result of the increasing urbanization of the region. Recent abstraction of GW from the deep aquifer has led to a decrease in the WT level by 15–20 m since the mid-1980s (Khadka 1993). The annual recharge in the Terai region of Nepal is 6–16 BCM, and the annual extraction is only 1 BCM, whereas in the Kathmandu valley, the annual recharge is only 5.5×10^{-4} BCM and the abstraction for domestic and industrial use is 1.8×10^{-3} BCM, creating an annual deficit of 1.3×10^{-3} BCM (verification-unit.org/./nepal./5-SPKhan_and_PS%20Tater_hydrogeologyandgroundwaterResoourcesofNepal.pdf). Extensive GW development for irrigation in the Terai plains started in the 1960s. Today, about 0.02 Mha are under GW irrigation by some 60,000 shallow tube wells and 1,000 deep tube wells, with a total GW abstraction of 700 m^3. About 200,000 shallow hand pump and tube wells now serve most of the 11 million population of the Terai plains.

The resource availability and development are not always in tune with each other (Figure 6.4); for example, in northwestern India, the dependence on pure tubewell irrigation does not match its resource availability, and there is much scope for further development in eastern India, the rest of Bangladesh, and Nepal's Terai region (Shah et al. 2006).

6.4 MAJOR CAUSES OF GW DEPLETION

In India, irrigation water and energy prices are highly subsidized by the government. GW for small-scale irrigation is also free to all farmers who can privately invest in tube wells and open wells (Singh 2001). These kinds of policies are the major reasons for the excessive use and the depletion

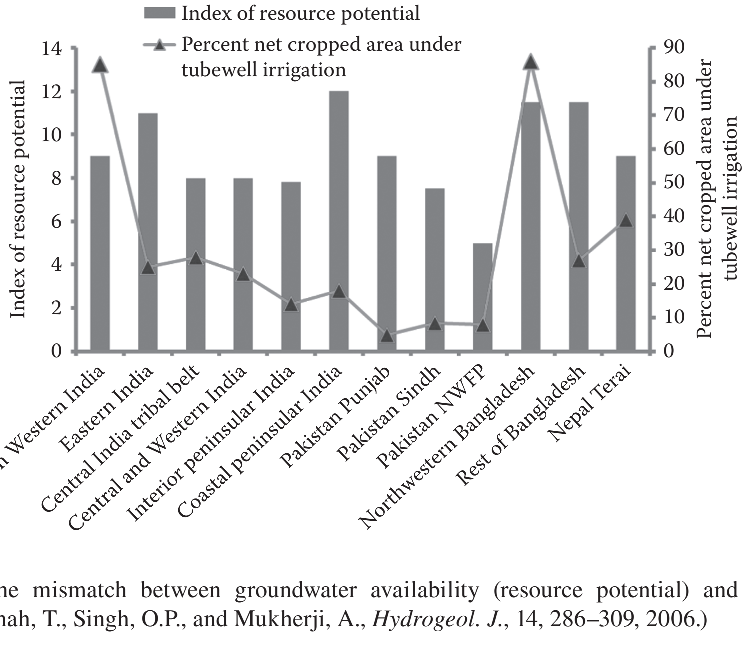

FIGURE 6.4 The mismatch between groundwater availability (resource potential) and development. (Modified from Shah, T., Singh, O.P., and Mukherji, A., *Hydrogeol. J.*, 14, 286–309, 2006.)

of GW reserves (World Bank 1993). With increasing investment in small-scale irrigation, the depletion of GW in many dry land villages is occurring at alarming rates. The basic incentive structures that induce overexploitation of GW are related to a lack of clearly defined and secure property rights that encourage cooperation (Shiferaw et al. 2003). This may eventually lead to overpumping and the exhaustion of the aquifer. The enormous development of bore wells also threatens aquifers and causes GW depletion, particularly in densely populated areas (Narain 1998). The GW policies are not in accord with the ground realities. There is less emphasis on the scarcity, depletion, and quality of GW. The enforcement of laws and administrative regulations are weak. Water rights are linked to land ownership. This virtually makes many aquifers open access resources to land owners (Shiferaw et al. 2003). The excessive and indiscriminate exploitation of GW has created a declining WT situation in the state. The problem is most critical in central Punjab. The average rate of decline over the last few years has been 55 cm/year. The worst affected districts are Moga, Sangrur, Nawanshahar, Ludhiana, and Jalandhar. This has resulted in extra power consumption, it affects the socioeconomic conditions of the small farmers, it destroys the ecological balance, and it adversely affects the sustainable agricultural production and economy of the state (Aggarwal et al. 2009). The major reason for this is a change in cropping pattern, for example, the introduction of HYV, urbanization, a decrease in the natural recharge, an increase in the population, industrialization, and more dependency on GW.

6.5 CONSEQUENCES OF GW OVEREXPLOITATION

6.5.1 Depletion of Aquifers and Crop Productivity

The most severe consequence of excessive GW pumping is the depletion of aquifers (Figure 6.5) and the subsequent lowering of the WT depth below which the ground is saturated with water, as observed in India's central Punjab, where the average WT depth decreased at a rate of 94 cm/year for the year 2004–2005 (Figure 6.6). The latest study of GW balance estimates shows that out of 138 development blocks, 103 fall in the "overexploited" category with a GW extraction of more than 100% of annual replenishment, 5 are classified as critical (stage of development 90%–100%), 4 are "semicritical" with a stage of development between 70% and 90%, and 25 are in the "safe" category with GW drafts of less than 70% of annual recharge. Block Nihalsinghwala in Moga District, for example, has the

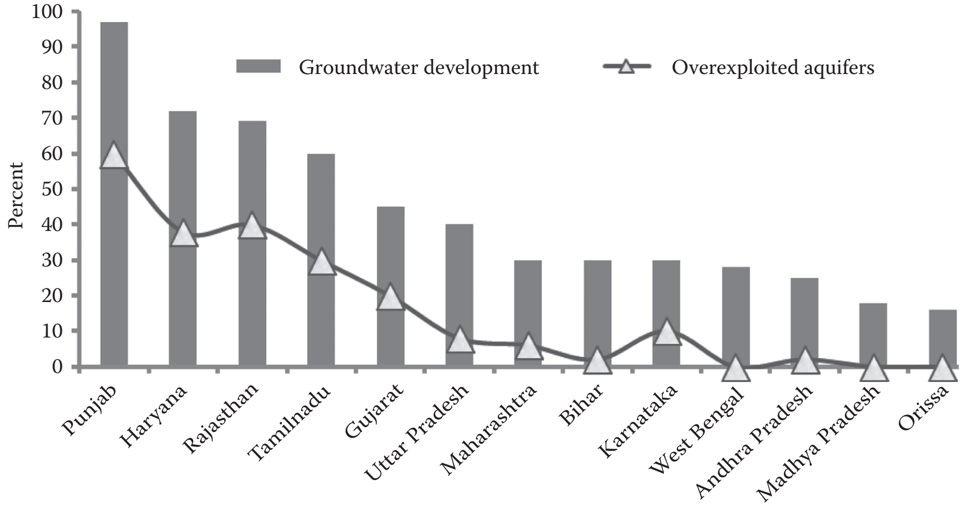

FIGURE 6.5 Groundwater aquifers in India are being depleted. (Modified from World Bank, *Revitalizing Punjab's Agriculture*, New Delhi, India, 2003.)

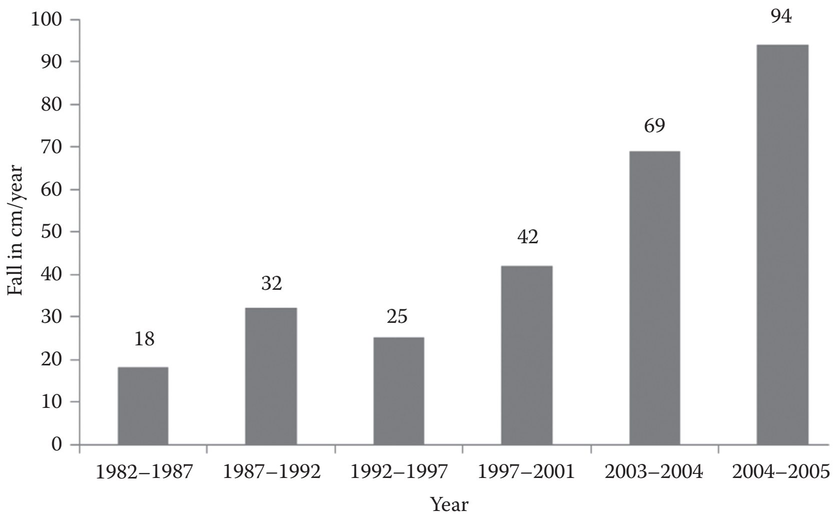

FIGURE 6.6 Average fall in the groundwater level in central Punjab, India. (Modified from Sidhu, R. and Vatta, K., Toward sustainable water use in India: Case studies from Punjab. New York, Columbia Water Center, 2010, water.columbia.edu/sitefiles/file/Uploads/Sidhu11-2010.pdf)

maximum stage of development of more than 200%. Safe blocks lie in southwest Punjab, where the GW is of poor quality, and in the Kandi area, where extraction is restricted due to deeper GW aquifers. Hira and Khera (2000) observed that in India's central Punjab, the percentage area with a WT depth of >10 m increased from 3% in 1973 to 53% and that with a WT depth of <5 m decreased from 45% to 5% for the same period because of the excessive mining of GW (Figures 6.7 and 6.8). The total number of tube wells in a small state like India's Punjab has increased from 192,000 to 935,000 over the 36 years between 1970 and 2006 (Table 6.7). The rate of depletion was less in the southwest zone as compared with the central zone due to the fast development of the canal network and better conjunctive use of surface water and GW (Table 6.8). About 75% of the state of Punjab is in the overexploited category, and only 18% is in the safe category (Figure 6.9). Thus, the WT in 90% of the Indian state of

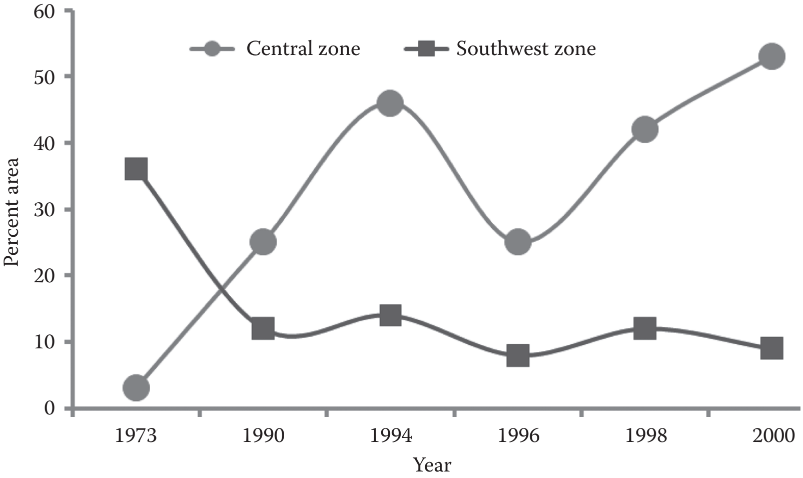

FIGURE 6.7 The increase in percent area with a water table depth of more than 10 m in the central zone of Punjab, India. (Modified from Hira, G.S. and Khera, K.L., Research Bulletin, Department of Soils, Punjab Agricultural University, Ludhiana, India, 2000.)

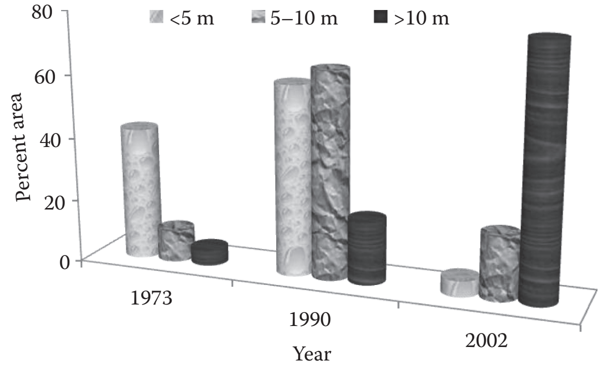

FIGURE 6.8 Percentage of area under different water table depths in central Punjab, India. (Modified from Hira, G.S. and Khera, K.L., Research Bulletin, Department of Soils, Punjab Agricultural University, Ludhiana, India, 2000.)

Punjab has decreased drastically since 1970. The WT was below 50 m in 2010, compared with 6–8 m in the 1970s. The key culprits are rice cultivation, the procurement price for rice, cheap labor, and the freedom to dig a tube well to get GW. The state government exacerbated the problem by supplying virtually free electricity, which resulted in intensive rice farming in Punjab. Paddies and wheat consume 66% of the total irrigation water (Hira et al. 2004). Recently, the Punjab State Farmers Commission has estimated that the aquifer level declined by about 4.7 m between 2001 and 2006 against 0.6 m between 1980 and 1986. In part of the state, the aquifer has declined over 10 m since the 1980s, which has many economic and ecological implications.

GW depletion is threatening the sustainability of the cropping system in the region. More electricity is required to withdraw water from lower depths (Figure 6.10), which increases the energy costs. GW depletion has directly impacted on the drying up of wells, the increased cost of pumping and well infrastructure, land subsidence (Galloway et al. 2001), salt-water intrusion, the changes in surface albedo, and related climate change (Ponce et al. 1997). The unsustainable use of GW will significantly impact a host of hydrological, ecological, and other natural resources and services,

TABLE 6.7
Number of Tube Wells (Million) in Punjab, India

Year	Diesel	Electric	Total
1970–1971	1.01	0.91	1.92
1980–1981	3.20	2.80	6.00
1990–1991	2.00	6.00	8.00
2000–2001	2.00	7.88	9.88
2001–2002	2.85	8.21	11.06
2002–2003	2.88	8.45	11.33
2003–2004	2.88	8.56	11.44
2004–2005	2.88	8.8	11.68
2005–2006	2.88	9.05	11.93
2006–2007	2.80	9.52	12.32

Source: Statistical Abstracts of Punjab. The Economic Advisor to Govt. of Punjab and Director of Agriculture, Punjab, 2008.

TABLE 6.8
Areas under Different Water Depths in the Central and Southwest Zones in Punjab, India: 1973–2000 (Percentage Area)

	Central Zone (Amritsar)			South-West Zone (Faridkot)		
Year	**<5 m**	**5–10 m**	**>10 m**	**<5 m**	**5–10 m**	**>10 m**
1973	39	58	3	39	25	36
1990	9	66	25	39	49	12
1994	6	48	46	30	56	14
1996	6	69	25	45	47	8
1998	6	49	42	45	43	12
2000	6	41	53	41	50	9

Source: Hira, G.S. and Khera, K.L., Research Bulletin, Department of Soils, Punjab Agricultural University, Ludhiana, India, 2000.

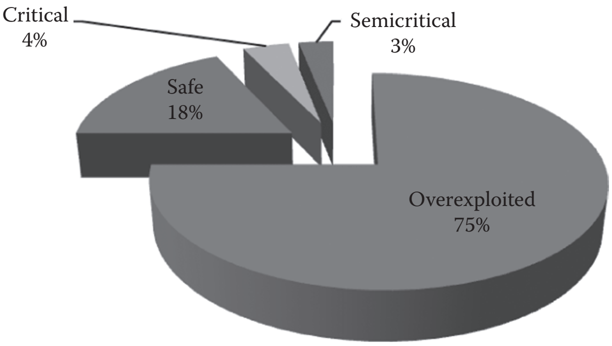

FIGURE 6.9 Extent of groundwater exploitation in Punjab. (From Jain, A.K. and Kumar, R., Water management issues—Punjab, 2007.)

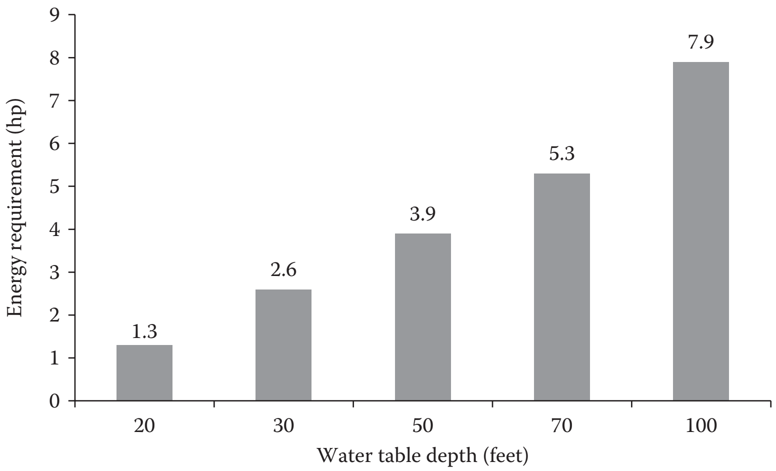

FIGURE 6.10 The increase in energy requirement with the increase in tubewell depth in Punjab, India. (Modified from Hira, G.S., Workshop papers presented in groundwater use in northwest India. Centre for Advancement of Sustainable Agriculture, New Delhi, India, 2004.)

including freshwater bodies, and aquatic, riparian, transitional, and terrestrial ecosystems. The GW depletion causes huge environmental, social, and economic costs. A few years ago, David Seckler, the then director general of IWMI, wrote alarmingly that a quarter of India's food harvest is at risk if the country fails to manage the GW properly. Today, many people think that Seckler might well have underestimated the situation, and that if India does not take charge of its GW, the agricultural economy may crash. The government initiatives to popularize deep bore wells to get more water have led to a drastic decline of the WT (Menon 2007). At the same time, there is neither interest nor any initiative in favor of recharging the GW. As the WT declines, poor farmers find it difficult to meet the huge energy requirement for deepening wells, which ultimately leads to a decline in food production.

6.5.2 Deterioration of GW Quality and Soil Salinization

Another adverse effect of the falling WT is the deterioration of the GW quality. The quality of the GW in the Indus Plains varies widely, both spatially and with depth, and is related to the pattern of GW movement in the aquifer (Qureshi et al. 2008). There are large numbers of saline GW pockets in the canal command areas of the Punjab and Sindh Provinces in Pakistan and the southwestern districts of India's Punjab. The GW is of poor quality in 23% of the area in Pakistan's Punjab Province and 78% in Sindh Province (Haider 2000). In the lower parts of the Indus Plains, the area of fresh GW is confined to a narrow strip along the Indus River. Similar situations exist in central areas of Punjab Province, where a layer of fresh GW floats over the saline water. Due to excessive pumping of this thin, fresh GW layer, the downward gradients are increasing, thereby inducing saltwater intrusion into the fresh GW areas. As a result of saline GW intrusion, about 200 public tube wells installed in the fresh GW zone of Pakistan's Punjab and Sindh Provinces had to be abandoned due to an increase in the GW salinity (EC: 10–12 dS/m). The salt-affected soils associated with the use of poor-quality GW for irrigation have become an important ecological disaster in India and Pakistan (WAPDA 2007). The potential to leach out the salt is very limited due to highly saline soils at shallow depths and highly saline GW at deeper depths (Bhutta and Smedema 2007). At present, 7 Mha of agricultural soils are affected by salt in India. Minhas (1996) observed that 32%–84% of the GW surveyed in different Indian states is rated either saline or alkaline. Because of the continental monsoonal climate, the basic principles of saline water management need some adaptation, for example, providing for a leaching requirement is not appropriate when the growing season for postmonsoon winter crops starts with a surface-leached soil profile, because it would increase the salt load. To minimize the salinity hazards in soils with a high WT, the salts are usually leached down and the waterlogging problems are alleviated by the installation of a subsurface drainage system. The use of GW by crops is also related to its depth and salt content (Chaudhary et al. 1974; Minhas et al. 1989, 1994).

6.5.3 Socioeconomic and Environmental Impacts

The declining WT and the soil degradation as a result of poor-quality GW use for irrigation have seriously affected the social and economic status of farmers in SA countries. The drying of wells has increased the burden of providing a livelihood for mankind. Women have to walk long distances to bring fresh drinking water from natural streams because the GW is very deep; sometimes, the GW is hazardous to health as it may contain heavy metals like As. Soil degradation caused by the use of brackish water has reduced the production potential of major crops by as much as 25%, valued at an estimated loss of US$250 million/year (Haider et al. 1999). The GW overdraft has also led to seawater intrusion in the coastal areas of the Indus Basin, and is threatening the wetlands ecosystems. Important aquatic resources, mangrove forests, and coastal areas need to be protected. Mangrove forests cover 130,000 ha; they are an important source of firewood and provide a natural breeding ground for shrimps and other wildlife.

6.6 EXTENT OF GW DEPLETION IN SA

6.6.1 India

Almost 54% of the GW blocks in the six states of India (i.e., Gujarat, Haryana, Maharashtra, Punjab, Rajasthan, and Tamil Nadu) are nearly depleted (*Economic Times* 2010). In fact, if the number of overexploited blocks continues to grow at the present rate of 5.5% per year, by 2018 roughly 36% of India's GW blocks will face serious problems. By 2030, 60% of the aquifers will be in a critical condition. Overexploitation is more prevalent in northwestern, western, and peninsular India (Shah 2002; Chatterjee and Purchit 2009). The status of GW development is comparatively high in northwestern India, where the stage of development is more than 100%, implying that in this region the average annual GW consumption is more than the average annual recharge. These states depleted, on average, 17.7 BCM of water annually, more than the government's estimate of 13.2 BCM in the same period. The GW depletion in the region was equivalent to a net irreplaceable loss of 109 BCM, or nearly 20% of Indians' annual water consumption of 634 BCM (Kerr 2009). Irrigation accounts for over 90% of water consumption in India, as is the case in many SA countries (Rosegrant et al. 2002; FAO 2003). Intensive agriculture leads to the depletion of GW resources, the buildup of salinity, waterlogging, the formation of hardpan (subsoil compaction), soil–nutrient imbalance, and an increased incidence of pests (Pingali and Rosegrant 2001). Some studies indicate that up to 50% of wells (especially open wells), once in use in many parts of India, have completely dried up. Agricultural economies built on the basis of GW irrigation may eventually collapse as nonsustainable water use leads to a depletion of the resource (Shiferaw et al. 2003). In India, the withdrawal of water for nonagricultural uses (i.e., domestic and industrial) accounted for 8% in the mid-1990s and is expected to increase to 14% by 2025 (Rosegrant et al. 2002). Although there are numerous strategies for the sustainable management of the GW resources, they often fail to create any positive impact on sustainable use for a number of reasons. Important among these is the absence of any pricing mechanism or strict regulation, indiscriminate GW exploitation, its wasteful utilization, and the land disposal of urban and industrial wastes (Menon 2007).

6.6.2 Pakistan

The availability of inexpensive drilling technologies allows even poor farmers to access GW to increase their crop production and improve livelihoods in Pakistan. The unreliability of the surface water supplies has turned more and more farmers to using GW without full awareness of the hazard represented by its quality. The trend of a continuous decline in the WT has been observed in many areas of Pakistan (Qureshi et al. 2009), illustrating the serious imbalance between abstraction and recharge. In the fresh GW areas of the Punjab and Baluchistan Provinces, the falling WT is a major issue. The excessive lowering of the WT has made pumping more expensive. As a result, many wells have gone out of production, yet the WT continues to decline and salinity continues to increase. In many areas of Balochistan, the WT is dropping at a rate of 2–3 m/year. Over 80% of the GW exploitation in Pakistan takes place through small capacity, private tube wells (Qureshi et al. 2010). These shallow tube wells (up to 6 m in depth) were initially installed by the farmers to capture the seepage from unlined canals to supplement their irrigation supplies for meeting the crop water requirements. Therefore, their installation and operational costs were very low and farmers were enjoying their benefits without much financial burden. However, the WT receded to depths that were inaccessible in 5% and 15% of the irrigated areas of the Punjab and Balochistan provinces, respectively. Under the business as usual scenario, this area is expected to increase to 15% in Punjab and 20% in Baluchistan by 2010 (PPSGDP 2000). With the receding WT depths (>15 m), farmers are left with no choice but to drill deeper wells. This transformation has increased the installation and operational costs. The construction cost of a deep electric tube well (>20 m) is US$5000 compared with US$1000 for a shallow tube well (<6 m). The present cost of pumping GW from a shallow tube well is US$4.2/1000 m^3 as compared with US$12/1000 m^3 from a deep tube well. Of course, all these costs are affected by the increasing energy prices. Beyond 20 m depth, turbine and submersible pumps are needed to extract the GW. The average cost of installation of such a pump is about US$10,000 in Balochistan and the maintenance of these deep tube wells is generally beyond the capacity of poor farmers. Under these conditions, access to GW has been restricted to large and rich farmers who can still afford this price. Thus, the sufferings of poor small farmers are further compounded. In Balochistan, the installation of more than 20,000 deep private tube wells over the last 10 years has negatively affected the traditional production systems. The declining WT has resulted in the desertification of the lands and the drying up of high-value fruit orchards. Qureshi et al. (2003) reported that more than 70% of the farmers in the Punjab Province depend directly or indirectly on GW to meet their crop demands. Over 80% of GW exploitation in Pakistan is in the private sector and there is no restriction or control on its abstraction. Nor is there a mechanism for allocating GW rights or for regulating its use. Anybody can install a tube well anywhere on his/her land and extract any amount of water at any time without consideration of the detrimental effects of this action on the resources and on others.

6.6.3 Bangladesh and Other South Asian Countries

In Bangladesh, fluctuations in the WT are drying up shallow wells, particularly during summer. This creates major difficulties for villagers in obtaining drinking-water supplies (Sadeque 1996), which has also had major inequity effects. While wealthy farmers can afford to deepen their existing wells or install new ones, resource-poor, small landholders cannot afford the cost of chasing the WT. There are also severe adverse environmental impacts. The dry-season flows at Farakha Barrage near the Bangladesh border could decline by about 75% if historical GW development patterns continue (Ilich 1996). Declines in the dry-season flow are a point of contention between India and Bangladesh. For Bangladesh, these flows are critical for irrigation, drinking-water supply, and for sustaining the mangrove areas along the coast. In Bangladesh's capital city Dhaka, the WT has dropped from 26.6 m in 1996 to 61.2 m in 2007, due to a lack of recharging, and this has put the sprawling metropolis at great risk. In Nepal, GW has declined by 15–20 m in the Kathmandu Valley due to excessive extraction and the use of GW for industrial and commercial purposes (www.ngoforum.net/index.php? option=com_content&task).

6.7 SUSTAINABLE MANAGEMENT OF GW IN SA

Food, water, and environmental security are the principal global issues of the twenty-first century. Although the stagnation and decline in agricultural production can be due to political and social reasons, the degradation of soil and water resources and the lack of appropriate technology to address the basic issues of resource mobilization and management are the primary factors responsible for low agricultural productivity (Lal 2000). Water scarcity and poor water quality are major concerns in SA countries, which mainly depend on agriculture for the livelihood of the people. Understanding the physics and hydrology of GW movement and measurement, the sociology and mindset of GW users, the economics of the water and agriculture sector, and the politics of the laws and the institutions are necessary for sustainable GW management (Shah 2007). Conjunctive use of the region's surface water and GW resources would help in minimizing the problems of waterlogging and GW mining (Shah 2000). Different approaches for the sustainable use of GW in SA are discussed next.

6.7.1 GW Management in India

India's GW governance pentagram is presented in Figure 6.11. The data on GW levels in India are neither widely published nor made available outside government organizations. Extraction and recharge estimates are also unreliable. As a result, discussions on GW depletion are always based on unreliable data (Menon 2007). The "boom and bust" in the GW-based agricultural economies has

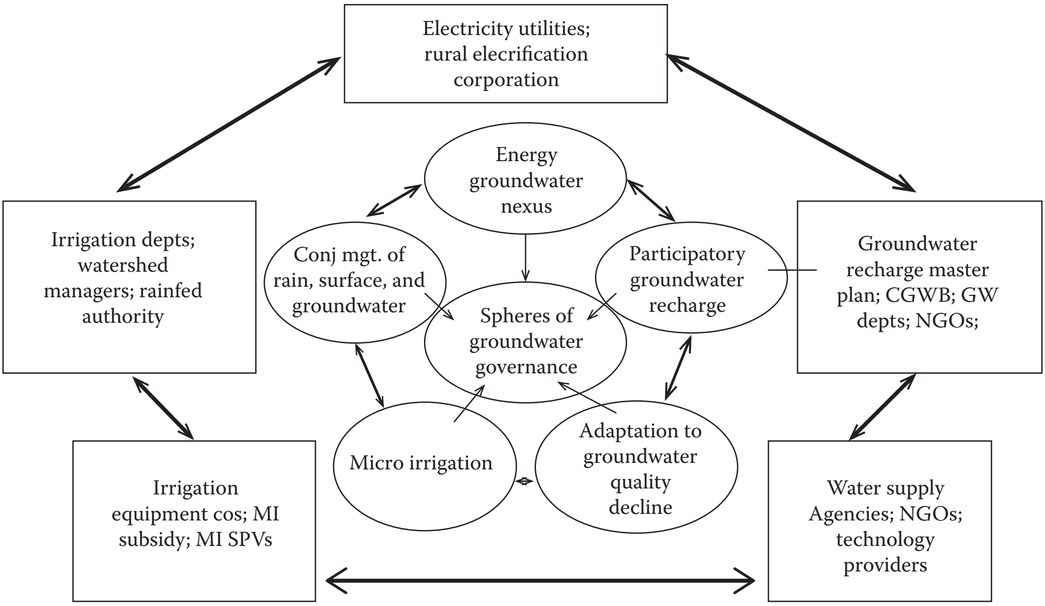
Electricity utilities; rural elecrification corporation
Energy groundwater nexus
Irrigation depts; watershed managers; rainfed authority
Conj mgt. of rain, surface, and groundwater
Participatory groundwater recharge
Groundwater recharge master plan; CGWB; GW depts; NGOs;
Spheres of groundwater governance
Micro irrigation
Adaptation to groundwater quality decline
Irrigation equipment cos; MI subsidy; MI SPVs
Water supply Agencies; NGOs; technology providers

FIGURE 6.11 India's GW governance pentagram. (Adapted from Shah, T., *Environ. Res. Lett.* 4, 035005, 2009a.)

been widely observed in India (Shah 2002; Rao et al. 2003). Economic incentives and water charges are needed to regulate GW abstraction and to shift cropping patterns toward water-saving options and to crops with high net water productivity. Programs of GW management must account for the current and future water requirements and the ecological, economical, and social costs of the overexploitation of the GW resources (World Bank 1999; Custodio et al. 2004).

6.7.1.1 Various Approaches for Efficient GW Management

In India, the different strategies on sustainable GW management clearly show that successful management needs an interdisciplinary and holistic approach, involving all stakeholders, technocrats, policy makers, and farmers. Further, hydrogeological conditions, local specific environmental issues, and indigenous methods of water conservation and usage must also be objectively assessed. There should be an effective policy framework that considers all the multidimensional aspects of the issues of water scarcity and overexploitation (Menon 2007). Such a framework must also include improving the public water supply, using energy pricing and supply to manage agricultural GW draft, increasing RWH and GW recharge, transferring surface water in lieu of GW pumping, increasing the economic growth, reducing the dependence on agriculture, and formalizing the water sector (Shah 2009b). An accurate assessment of the available surface water and GW resources, considering the anthropogenic changes, is needed for the planning, designing, and operationalizing of the water resources projects as well as for watershed management. There should be a periodic reassessment of the surface water and GW potential on a scientific basis, taking into consideration the quality of the water available and the economic viability of its extraction (MWR 2009). In critically overexploited areas, bore well drilling must be regulated until the WT attains the desired level. The sustainability of GW utilization must be assessed from an interdisciplinary perspective because hydrology, ecology, geomorphology, climatology, pedology, agronomy, and economics play important roles (Ponce 2006). These interdisciplinary aspects of GW utilization have brought into question the concept of safe yield, defined as the maintenance of a long-term balance between the amount of withdrawal and the amount of recharge (Sophocleous 2000). Thus, the issue of GW sustainability is critical to overall development (Alley and Leake 2004). As a dynamic and replenishable resource, the GW has to be estimated primarily based on the component of annual recharge. The later is subjected to development by means of suitable structures whose choice depends on the hydrogeological and climatic conditions. The exploitation of GW resources must be regulated so as not to exceed the recharging possibilities, as well as to ensure social equity. The detrimental environmental consequences of overexploitation of GW need to be effectively prevented by the central and state governments (Jain et al. 2007).

6.7.1.2 Institutional Capacity Building

Another means of enhancing the use efficiency of GW is through institutional capacity building. This involves empowering and equipping people and organizations with the appropriate tools and sustainable resources to address their problems (Reddy and Vijaya Kumari 2007). Clearly, a joint management approach combining government administration with active people participation is a promising solution.

6.7.1.3 Proper Development of GW Resources and Interbasin Transfers

GW management not only requires the proper assessment of the available resources and an understanding of the interconnection between the surface water and GW system, but also actions for proper resource allocation and prevention of the adverse effects of the uncontrolled development of GW resources. In many parts of the country, deep aquifers are not fully utilized or developed, leading to underutilization of the available GW resources (Table 6.9). It is estimated that the basin transfer of water from surplus to deficit basins, by linking rivers in the northern region to those in the eastern region, may increase the irrigation potential. Such an undertaking, however, must be done on a win-win basis for all states concerned (MWR 2006). Policy makers often pay attention to the regions where GW development has the greatest potential and neglect the regions with low or hidden potential. In India, the eastern and northeastern regions are yet to develop their GW resources (Menon 2007). Yet, there is wide scope for the development of GW in these areas, which often faces floods during the rainy season. Ironically, some regions of India are suffering from flood damage and other regions are prone to acute and perpetual water shortages. Karnataka, Tamil Nadu, Rajasthan, Gujarat, Andhra Pradesh, and Maharashtra are the worst drought-prone states. Uttar Pradesh, Bihar, West Bengal, Orissa, and Assam face severe flooding. The interbasin transfer of water in India is a long-term option to partly overcome the spatial and temporal imbalance of the availability and demand of water resources (Kumar et al. 2005). Flood plains are good reservoirs of GW. Thus, the sustainable management of flood plain aquifers offers excellent scope for its development and the additional requirement of water. The development of GW in the Yamuna flood plain area in Delhi is an example of the scientific management of resources (Shekhar and Prasad 2009). The waterlogged

TABLE 6.9
Availability of Surplus/Unutilized Groundwater in the Eastern States of India

State	Net Annual Groundwater Availability (BCM)	Annual Groundwater Draft (BCM)	Annual Groundwater Available as Surplus/Unutilized	
			BCM	(%)
Assam	24.9	5.5	19.5	78
Bihar	27.4	10.8	16.7	61
Chhattisgarh	13.7	2.8	10.9	80
Jharkhand	5.3	1.1	4.2	79
Orissa	21.0	3.9	17.2	82
West Bengal	27.5	11.7	15.8	58
Punjab	21.4	31.2	−9.7	−45

Source: National Rainfed Authority Area, Food security, water and energy nexus in India, 2008. www.corecentre.co.in/Database/Docs/DocFiles/food_security.pdf.

areas in canal commands offer scope for GW development by lowering the WT by up to 6 m or more. One of the effective strategies for sustainable GW management is to use surface water in one area, utilizing the recharge by developing GW in areas adjacent to the canal commands.

6.7.1.4 Artificial Recharge and RWH

There is a need to recharge aquifers and conserve rainwater through the installation of RWH structures (Sivanappan 2006). In urban areas, rainwater can be harvested from rooftops and open spaces. RWH reduces the possibility of flooding, and also decreases the community's dependence on GW for domestic uses. Apart from bridging the demand–supply gap, recharging improves the quality of the GW, raises the WT in wells and bore wells, and prevents the flooding and choking of drains. One can also save energy to pump GW as the WT rises due to recharging of the wells. In many states in India, RWH is being undertaken on a massive scale. Substantial benefits of RWH exist in urban areas as water demand has already outstripped the supply in most cities. It is estimated that, annually, about 36.4 BCM of surplus surface runoff can be recharged to augment the GW (Romani 2005). In rural areas, techniques are demonstrating the feasibility of artificial recharge by modifying the natural movement of the water through suitable civil structures (e.g., percolation tanks, check dams, stream bunds, and gully plugs). The government should take initiatives, such as offering soft loans and passing legislation to install devices in all new government and private buildings to promote the RWH system. Moreover, publicity and training are a must to make people aware of the rainwater quality and the harvesting system. The collected rainwater could be used for washing, gardening, and toilet flushing without prior treatment. Areas that suffer from a severe shortage of water could use the RWH system for domestic water uses (potable water). Harvested water can be treated by chlorination, solar or UV radiation, or heating prior to human consumption. The states of Karnataka, Andhra Pradesh and Tamilnadu have over 200,000 tanks, and a strategy that has been widely recommended is to transform these tanks into recharge tanks by filling them up with canal water (Kulandaivelu and Jayachandran 1990; Reddy et al. 1990). In the western region of India, local NGOs and communities have spontaneously created a massive well-recharge movement based on the principle of "water on your roof, stays in your compound; water on your field stays on your field; and water on your village, stays in your village." People have modified some 300,000 wells—open and bore—to divert rainwater to them; they have also constructed thousands of ponds, check dams, and other RWH and recharge structures on the self-help principle to keep the rainwater from gushing into the Arabian Sea (Shah 2000). Percolation of a portion of the rainfall, through the vadose zone, is the principal source of natural recharge to the aquifer systems in India. The recharge rates range from 4.1% to 19.7% of the local average seasonal rainfall (Rangarajan and Athavale 2000). Annually, some 1150 BCM (out of a total annual rainfall of 4000 BCM) of India's rainwater runs off into the seas (INCID 1999; Kumar 2006). It is necessary to hold this water by reducing the velocity of the runoff and providing time for recharge and enhancing the GW availability. Check dams, village ponds, rooftop water harvesting, and interlinking different rivers are some options to increase the GW recharge. The sustainable use of GW should begin by tapping primarily deep percolation and secondarily shallow percolation. The latter should be exploited only if its effects on the base flow of the neighboring streams and water bodies are minimal. Detailed hydrological and hydrogeological studies are required to determine the percolation amounts. In the Indian watersheds, the public and watershed communities pay the investment costs needed to recharge the GW. A number of check dams are built in each watershed at selected locations along the watercourse to retain the stream flow and increase the infiltration into the ground (Kerr et al. 2002). In the coastal desert of North Chile, a fog collection project has been able to provide an average of 11,000 L/day of water to a community of 330 people (Schemenauer and Cereceda 1991).

6.7.1.5 Effective Water Pricing on GW

Subsidized energy prices, open access externalities, low pumping costs, and free access to water jointly encourage GW overpumping and depletion; therefore, water charges may be considered a suitable policy option to promote water saving and to counter depletion (Shiferaw et al. 2003). In India, irrigation water is charged (partly) only for public sources (i.e., canal and tank irrigation systems). There is considerable diversity in the system of levying irrigation charges across states (Sampath 1992). The rates are often levied on the basis of the area irrigated, differentiated by crop and season, but may be uniform throughout the state (FAO 2003). Generally, in the presence of pumping subsidies, the rates are small and small-scale private tube- and open well irrigation systems are exempted from payment. Regardless of its scarcity, water is a free resource to all smallholder farmers who are able to invest in the infrastructure to tap existing aquifers. With the increasing scarcity, local informal markets have developed in some areas, where water-deficient farmers rent water seasonally from water-surplus farmers (Shah 1993; Meinzen-Dick 1998; Saleth 1998; Shah et al. 2003b). The water rates may vary by season and the type of crop grown. As much as 25% of the output is paid for irrigation water. In some cases, payments may occur based on the hours of irrigation. The removal of price and energy subsidies for pumping GW and the proper costing of the public irrigation services are critical policy instruments for managing the demand (Shiferaw et al. 2003; Scott and Shah 2004). For smallholder agriculture, the actual levels of GW extraction and use are not metered and hence cannot be directly observed. Therefore, farm-level direct volumetric charges are infeasible. Many farmers consider free and unrestricted access to GW a fundamental and ancestral right. Despite the efforts of community watershed management projects to regulate water use, this entrenched perception of private rights has contributed to the lack of cooperation and to the dramatic increase in unregulated small-scale irrigation. The incentive-based approach is likely to perform better than the regulatory approach, while also providing higher and sustainable economic benefits from water conservation to small farmers (Schaible 2000; Tiwari and Dinar 2002). Two incentive-based approaches are (1) charges based on hours of irrigation, and (2) charges per unit of output. The first is directly related to the volume of water used. The second is related to the productivity of water. The water charges should be large enough to shift the cropping patterns to high-value and water-efficient crops and induce efficient and judicious use of the GW. Since farmers do not pay (or pay a minimal flat rate) energy tariffs, the water charges can be considered to include the energy prices for pumping. Water-deficit farmers in SA buy water seasonally from adjacent farmers through various informal arrangements (Saleth 1998; Meinzen-Dick 1998). As in land contracts, the transactions may vary from in-kind labor contracts to upfront cash payments. The fixed share approach rather than a fixed quantity or cash rental is preferred perhaps due to its risk-sharing benefits. Unlike the area-based approach, it also allows flexibility in crop choice and permits actual payments to vary according to the crop grown. When water is free to irrigating farmers, it leads to the shifting of cropping patterns to more intensive crops (e.g., rice), which should not be encouraged in water-scarce areas. For the semiarid production systems discussed here, irrigation seems to be an attractive option until the water charges reach about Rs. 25–30 per h ($0.55) (Shiferaw et al. 2003). Alternatively, the output share charges could be increased up to 20%. If the water charges are reinvested in improving the availability of water, small farmers will directly benefit from them. Even while subsidizing electricity, many state governments have begun restricting the power supply to agriculture to cut their losses. Shah (2007) reported that IWMI studies have shown that with the judicious management of the power supply to agriculture, the energy–irrigation nexus can be a powerful tool for GW demand management in livelihood-supporting socioecological conditions to create tradable property rights in GW. Even as governments evolve the GW regulations and their enforcement mechanisms, more practical strategies for GW governance need to be evolved in five spheres, as outlined in Figure 6.11. Synergizing the working of agencies in these spheres offers the best chance to bring a modicum of order and method to the region's water-scavenging irrigation economy (Shah 2009a).

6.7.2 GW RESOURCE MANAGEMENT IN PAKISTAN

In addition to institutional reforms, supply and demand management approaches also need to be followed in Pakistan (Qureshi et al. 2010). For demand management, farmers must adopt improved irrigation and agronomic practices. Current land-use patterns must be reviewed to replace water-intensive crops with water-efficient crops. For supply management, the use of wastewater and saline drainage effluents for agriculture can be promoted. In rainfed areas, more efforts should be focused on RWH. The effective coordination between organizations responsible for the management of GW resources also needs to be enhanced. Van Steenbergen (2002) reported the benefits of local GW management through the use of social norms in Baluchistan, Pakistan. The irrigation system brought water through karezes (a form of subterranean aqueduct) from the subsurface flow of the river and from the infiltrated runoff from the surrounding hills. Typically, no well may be dug within 5 km of an existing subterranean aqueduct.

6.7.2.1 Use of Alternate Water Resources

Some parts of Pakistan suffer from the problem of brackish water, and studies show that this water can be used for irrigating a range of crops grown in different soil types under diverse environmental conditions (Sharma and Rao 1998; Qadir et al. 2001). Brackish GW has been successfully used to irrigate wheat, cotton, pearl millet, sugar beet, etc. Yield reductions of up to 15%–20% have been observed when compared with freshwater irrigation. In the deep GW areas, the excessive accumulation of salts is adequately managed during the summer monsoon rains. In shallow GW areas, properly managed drainage systems are mandatory for the successful use of brackish water for irrigation without causing soil salinization.

6.7.2.2 Promoting RWH

The rainfed areas of Pakistan contribute about 10% of the total agricultural production. However, the production levels of the rainfed areas are low (i.e., 1–1.5 Mg/ha). Yet, the production potential of these areas can be doubled by providing one or two supplemental irrigations at the critical growth stages of the crop (Oweis and Hachum 2001). Wherever farmers are already using supplemental irrigation, it is being done through GW extraction. However, farmers should be encouraged to adopt RWH and watershed management strategies to both improve the productivity of the rainfed systems and reduce the demands on the GW. While many fragmented efforts have been made in the past, there is a need to develop a comprehensive policy at the government level to ensure continuity in this regard. Furthermore, farmers must be educated to optimize the crop yields by using less water rather than maximize it through excessive GW irrigation.

6.7.2.3 Managing Conjunctive Use of Surface Water and GW

In most of the canal command areas in Pakistan, the conjunctive use of surface water and GW is equally practiced in the head and tail ends of the canal system. The canal water delivered to the head-end farmers is generally 32% and 11% more than to the farmers at the tail end and middle end, respectively (Haider et al. 1999). The unmanaged conjunctive use of surface water and GW at the head ends of the canals causes the WT to rise, resulting in waterlogging, whereas at the tail ends, salinity problems are increasing due to the excessive use of bad quality GW for irrigation. Therefore, planned conjunctive use is needed, whereby the upstream farmers make better use of the surface supplies in the canals, which are more reliable for them. For this purpose, the canal department needs to regulate the canal flows to match the crop water requirements. The inferior quality water can be mixed with the canal water in a proportion acceptable for irrigation (Hussain et al. 2010). Farmers also need to be educated on the proper mixing ratios of the surface water and GW resources in order to keep the salinity of the irrigation water within permissible limits and to avoid the risk of secondary salinization.

6.7.3 MANAGING GW POLLUTION IN BANGLADESH

A comprehensive water distribution system and a national water resources management policy need to be implemented to limit the indiscriminate extraction of GW in Bangladesh. An efficient monitoring system should also be established to ensure the supply of potable water throughout the country, and to prevent further As contamination in drinking water. For the overall improvement of the present As disaster in Bangladesh, it is highly recommended that every donor project of As mitigation be legally required to ensure community participation in water resources management. In any water supply and As mitigation project, water resources management with the involvement of the local community would play an important role in the remediation of GW As contamination. The rapid population growth and the lack of overall coordination have increased the demand for water and created ethnic conflicts. The widening gap between the demand and the supply of water is causing severe socioeconomic and environmental problems in Bangladesh. The organizations concerned with water resources management have failed to attain the required level of efficiency. Their failure in water resources management has played a major role in creating the As contamination in Bangladesh and elsewhere in SA. The As contamination of Bangladesh's GW with its genesis and toxic effects on humans has been widely reported (Dhar et al. 1997; DCH 1997; Karim et al. 1997; Nickson et al. 1998; Ahmed 2000; Karim 2000). Several studies indicate that the GW is severely contaminated with As above the maximum permissible limit of 0.05 mg/L for drinking water. About 400 measurements conducted in Bangladesh in 1996 (Smith et al. 2000) indicate that As concentrations in about half of the measurements were above the maximum permissible limit. In 1998, the British Geological Survey (BGS) collected 2022 tubewell water samples from 41 As-affected districts (Smith et al. 2000). Laboratory tests revealed that 35% of these water samples had As concentrations of >0.05 mg/L. In order to mitigate the As disaster, it is essential to treat As-contaminated water and water sources or to avoid using the As-contaminated water. The removal of As from water is possible by ultraviolet radiation, oxidation, chemical precipitation, and filtration (Safiuddin and Karim 2001). Further, As-contaminated soils and shallow GW aquifers could also be cleaned by flushing out the As contaminants. The avoidance of As is also feasible by the use of surface water, rainwater, and alternative GW sources.

6.8 RISING WATER LEVEL AND WATERLOGGING IN SA

Similar to the problem of GW depletion in many parts of SA, there is also the problem of a rise in the WT in parts of India and Pakistan. However, it is difficult to evaluate the extent of the problem based on the available data. In India, the Ministry of Agriculture estimated that the total area affected by waterlogging as a result of both GW rise and poorly controlled irrigation was 8.5 Mha in 1990 (Vaidyanathan 1994). By contrast, the Central Water Commission for 1990, which considered only the areas affected by a GW rise, estimated the waterlogged areas at 1.6 Mha (Vaidyanathan 1994). Regardless of the actual extent, waterlogging represents a major challenge in surface water and GW management. This challenge cannot be addressed in the absence of an integrated approach that incorporates surface water imports and use in conjunction with that of the GW. Large areas of Pakistan face similar problems. The rising WT in the command of surface irrigation systems has fundamental implications on the sustainability of social objectives in the GW-dependent regions. Irrigation-induced salinity and waterlogging reduce crop yields in Pakistan by 30% (FAO 1997). In India, the problem is serious enough to threaten the growth of the agricultural economy (Joshi et al. 1995).

The adverse impact of waterlogging and salinization on farmers and regional economies can be insidious. Initially, the introduction of irrigation often causes a dynamic transformation of the regional and household economies. Farmers introduce HYV of crops and are able to grow valuable market/cash crops. Wealth is created. However, as the WT rises, the "bubble economy" based on unsustainable water management practices deflates. Once salinized, the land and the unsaturated zone of the soil are difficult and expensive to reclaim. Ultimately, many farm families (and regional economies) may be worse off than before the introduction of irrigation unless sustainable and affordable methods of remediation are used. In India's Punjab, the problem of a rise in the WT and a salt buildup has been caused in the southwestern districts (Bajwa and Josan 1989) because of seepage from unlined canals and poor drainage facilities. Moreover, the GW of the region is brackish, for example, saline-sodic water (Minhas and Gupta 1992), and farmers mostly use canal water for irrigation. The seepage from the unlined canals has raised the WT in the entire region.

6.9 CLIMATE CHANGE IMPACTS ON GW IN SA

Global climate change may also profoundly affect hydrologic systems worldwide. Glacial melting and increasing ocean temperatures lead to a rise in the sea level. The changes in temperatures and rainfall influence the growth rates and the leaf size of plants, which affect the GW recharge (Kundzewicz and Doll 2007). Changing river flows in response to the changing mean precipitation, the rising sea levels, and the changing temperatures will influence the natural recharge rates (http://www.gwclim.org/ presentations/plenary/kundzewicz.pdf). In the SA region, particularly India, the frequency and severity of floods and droughts are expected to increase, while higher temperatures will reduce the winter snow pack and hasten the spring snowmelt from mountainous areas (Kumar et al. 2005). Climate change may increase uncertainties in the supply and management of water resources. Temperature increases affect the hydrologic cycle by directly increasing the evaporation of the available surface water and vegetation transpiration. Consequently, these changes can influence the precipitation amounts, the timings and intensity of rains, and indirectly impact the flux and storage of water in surface and subsurface reservoirs (i.e., lakes, soil moisture, and GW). In addition, there may be other associated impacts, such as seawater intrusion, water quality deterioration, and potable water shortages.

GW resources are related to climate change through direct interaction with surface water resources, such as lakes and rivers, and indirectly through the recharge process. The direct effect of climate change on GW resources depends on the change in the volume and distribution of the GW recharge. Therefore, quantifying the impact of climate change on the GW resources requires not only the reliable forecasting of changes in the major climatic variables, but also an accurate estimation of GW recharge (www.angelfire.com/nh/cpkumar/publication/CC_RDS.pdf). Unchecked, GW depletion can exacerbate the impacts of these changes; conversely, controlled management of GW depletion can contribute to their mitigation. Assuming that the volume of GW depleted during the past 100 years is much greater than what can be accounted for by nontransient increases in the volumes of water stored in the soil, natural channels and lakes, or the atmosphere, then the ultimate sink for the "missing" GW is the oceans. Worldwide, the magnitude of GW depletion from storage may be so large as to constitute a measurable contributor to the rise in sea level. For example, the total volume depleted from the High Plains Aquifer equates to about 0.75 mm, or about 0.5%, of the observed sea-level rise during the twentieth century (Konikow and Kendy 2005).

Climate change will act as a force multiplier; it will enhance the GW criticality for drought-proofing agriculture and simultaneously exacerbate the threat to the resource. From a climate change point of view, India's GW hotspots are western and peninsular India. These regions are critical to climate change mitigation as well as adaptation (Shah 2009a). A long-term temperature rise will increase the need to store water for distribution over a longer dry season. In some areas, an integrated solution can be achieved by artificially recharging the excess runoff, when available. Thus, depleted aquifers can be transformed into underground "reservoirs" to supplement the flood-buffering and drought-buffering capacity of the existing surface water reservoirs. Under a changing climate scenario, the annual variability in the monsoon's precipitation levels will increase to more intense floods and droughts. Thus, climate change in the future is expected to have implications on the river flows in SA (especially India), which will directly affect the GW status.

The developing countries of temperate and tropical Asia are already highly vulnerable to extreme climate events, such as floods, droughts, and cyclones. Climate change and variability would exacerbate these vulnerabilities. The GW management approaches for effectively dealing with climate change will have to be different from those that have been used in the past. Climate change due to global warming is increasing the complexities and vulnerability of food security in irrigated and rainfed agriculture, both in developing and developed countries (Brown and Hansen 2008; FAO 2008).

6.10 CARBON FOOTPRINTS OF SA'S GW ECONOMY

GW pumping with electricity and diesel accounts for an estimated 16–25 Tg of C emissions (Shah 2009a), which is 4%–6% of India's total C emissions. Total electricity consumption in GW irrigation is 87 billion kWh. GW pumping in India results in the emission of 14.38 Tg of C (i.e., 11.09 Tg by electric pumps and 3.29 Tg by diesel pump sets). The IFPRI (2009) estimates that the use of coal-based electricity as well as diesel fuel to pump the GW for irrigation are major sources of CO_2 emission. The IFPRI estimates that the C emission from GW irrigation is higher at 16 Tg, roughly 4% of India's total C emissions, and reducing the subsidies on the electricity used to pump GW for irrigation would lower the CO_2 emission by 14% (IFPRI 2009). Two interesting aspects of the C footprint of India's GW economy are as follows. (1) Lifting 1000 m^3/m of water using electricity emits 5.5 times more C than using diesel, and diesel pumps are concentrated in eastern India with rich alluvial aquifers. (2) The C emission from GW irrigation is highly sensitive to the dynamic head over which GW is lifted because, for one, a higher head leads to higher energy use and higher C emissions, and second, beyond a depth of 10–15 m, the diesel pumps become extremely inefficient, forcing irrigators to switch to electricity, which has a larger C footprint anyway (Shah 2009a). Most of India's diesel pumps are concentrated in eastern India and electric pumps are concentrated in western and peninsular India. Deep tube wells have a high C footprint (IFPRI 2009; Nelson et al. 2009). Climate change and GW discussions are at a very early stage in India. However, preliminary studies show massive scope for reducing the C footprint of India's GW economy. Using data from Haryana and Andhra Pradesh, Shukla et al. (2003) reported that every 1 m decline in pumping the WT increases greenhouse gas (GHG) emissions by 4.4% in Haryana and 6% in Andhra Pradesh. The most important determinant of the C footprint of India's pump irrigation economy is the dynamic head over which farmers lift water to irrigate the crops. The larger the head, the higher the energy consumption and the more likely that electrified deep tube wells are used for pumping GW, multiplying the C footprint of GW pumping. The C emissions to lift 1000 m^3 of water to 1 m are 0.665 kg C with diesel-fueled pumps and 3.873 kg C with electric pumps (Nelson et al. 2009). Deep wells powered by electricity are the largest single source of CO_2 emissions. They accounted for 65% of the total in 2000 and are projected to account for 87% in 2050. The 38 million mt of CO_2 emitted from deep well pumping accounted for more than 5% of India's total GHG emissions from all sectors of the economy in 2000 (World Resources Institute 2009). As expected, both higher transmission losses and deeper wells result in more CO_2 emissions. The increase in transmission losses raises CO_2 emissions by about 11%. Deeper wells increase emissions by 33%. Pump efficiency has the most dramatic effect on our estimates of carbon emissions. If pumps are only 20% efficient instead of the 30% assumption of the baseline, carbon emissions increase by 50% over the baseline (Nelson et al. 2009).

6.11 CONCLUSION

The sustainable management of GW offers opportunities for alleviating hunger and enhancing the livelihood of the SA population. However, there is a dire need to use and restore this vital resource through judicious management. A big part of the solution is massive initiatives to augment GW recharge in regions suffering from depletion throughout SA. However, this strategy cannot work without the appropriate demand-side interventions. The removal of price and energy subsidies for pumping GW and the proper costing of public irrigation services are critical policy instruments for managing this vital resource. There is a need for proper legislation to make RWH mandatory for public and private buildings, especially in urban areas. There should be awareness creation about the significance of recharging GW among the public through various media. There is a need to change the mindset by shifting water management skills from resource development to resource planning. All users of water should conduct a water audit to see how water can be saved and used. Wastewater can also be effectively recycled and reused by facilitating ecological activities. There is a strong need to monitor the database related to the GW properties and variables necessary to detect significant trends, using modern tools to generate relevant and accurate data. Because of the changing scenarios, a regular reassessment of the GW resources is essential, and this requires strengthening of the available database. Therefore, the judicious management of GW is an important strategy. Encouraging and implementing artificial recharge, conservation, water-saving irrigation, growing less-water-requiring crops, the conjunctive use of surface water and GW, fresh and brackish water, treatment and reuse of wastewater, and land-use planning and land zoning as per the availability of water, and taking appropriate measures to avoid pollution are all important. A proper capacity buildup and raising public awareness by better communication, coordination, and collaboration with water managers, planners, decision makers, scientists, and water users will help in better GW management. There is a need to establish a legal and regulatory framework regarding the development and use of GW by revising the policies on subsidized and free power in the agricultural sector. These problems must be addressed in view of the increasing risks of water pollution and contamination (i.e., As) and the changing climate of the SA region.

ABBREVIATIONS

BCM	Billion cubic meters
BGS	British Geological Survey
CPWF	Challenge Program on Water and Food
DCH	Dhaka Community Hospital
FAO	Food and Agricultural Organization
GOP	Government of Pakistan
GR	Green revolution
GDP	Gross domestic product
GW	Groundwater
HYV	High yielding varieties
hp	Horse power
IWRS	Indian Water Resources Society
INCID	Indian National Committee on Irrigation and Drainage
IFPRI	International Food Policy Research Institute
MWR	Ministry of Water Resources
PWP	Pakistan Water Partnership
PPSGDP	Punjab Private Sector Groundwater Development Project
RWH	Rainwater harvesting
SA	South Asia
WAPDA	Water and Power Development Authority
WPB	Water policy briefing
WT	Water table

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7 Water Resources and Agronomic Productivity in the West Asia and North Africa Region

Mostafa Ibrahim, Rattan Lal, ElSayed Abdel Bary, and Atef Swelam

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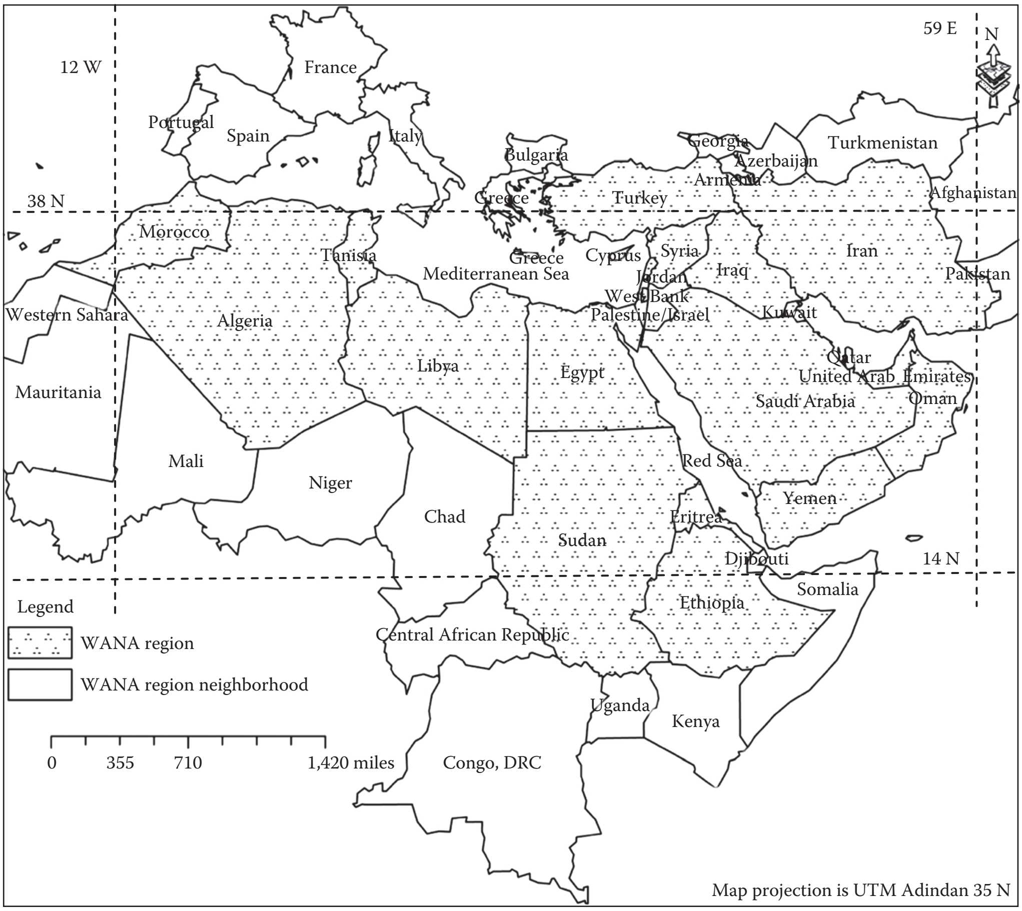
7.1 INTRODUCTION

The West Asia and North Africa (WANA) region comprises a large part of the Middle East and spans over two continents (Africa and Asia) ranging from 14° to 38° north and 12° west to 59° east (Figure 7.1). Geographically, it spans from the Atlantic Ocean in the west to the Arabian/Persian Gulf in the east and the Mediterranean Sea in the north to the Arabian Sea and Indian Ocean in the south (Figure 7.1). The region includes 22 different countries: Algeria, Bahrain, Cyprus, Egypt, Eritrea, Ethiopia, Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, Turkey, the United Arab Emirates (UAE), and Yemen. The region's land area covers 1584 million hectare (Mha) or 10.6% of the world land area (Table 7.1). The cultivated area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Mediterranean Sea
Jordan
West Bank
Palestine/Israel
Kuwait
Western Sahara
Algeria
Libya
Egypt
Qatar
United Arab Emirates
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Mali
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FIGURE 7.1 The West Asia and North Africa (WANA) region and its neighborhood. (Data from Iowa State University, CRP 551 Course. Created by M. Ibrahim, 2011.)

covers 124.83 Mha or 7.9% of the region's total land area. A wide variation in the total and cultivated areas occurs at the individual country level. For example, Bahrain and Cyprus have the smallest land areas of 0.08 and 0.93 Mha, respectively. By contrast, Algeria and Sudan have the largest land areas of 238.17 and 250.58 Mha, respectively (Table 7.1).

The WANA territory is geographically categorized into five regions: the North Africa region (Algeria, Libya, Morocco, and Tunisia), the Nile Valley/Red Sea region (Egypt, Eritrea, Ethiopia, and Sudan), the West Asia region (Cyprus, Iraq, Jordan, Lebanon, and Syria), the Highlands region (Iran and Turkey), and the Arabian Peninsula region (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the UAE, and Yemen).

Most of the WANA region countries are characterized by their arid and semiarid climate. However, the large area is composed of diverse climatic regimes. Four broad climatic regions can be distinguished in this large area. The arid region comprises 46.6% of the total land area with a mean annual precipitation (MAP) of 100 mm; the semiarid region comprises 21.9% of the total land area with a MAP of 100–300 mm; the semimoist region comprises 19.7% of the total land area with a MAP of 300–500 mm; and the moist region comprises 12% of the total land area with a MAP of more than 500 mm. The mean annual temperature (MAT) of the region ranges from 11.4°C in Turkey to 29.2°C in Sudan and Yemen (Table 7.1).

The cultivated land area is currently constant, but it could decrease either quantitatively or qualitatively through desertification by land misuse, soil mismanagement, and land use change (urbanization). Similarly, water resources, especially fresh water, which is composed of surface water and groundwater,

TABLE 7.1
General Facts about Countries of the Region

Country	Location[a]		Total Area[b]	Cultivated Area		MAP (mm)	MAT[c] (°C)
	Long.	Lat.	($\times 10^6$ ha)	($\times 10^6$ ha)	(%)		
Algeria	3°00′E	28°00′N	238.17	8.42	3.54	89	16.8
Bahrain	50°33′E	26°00′N	0.08	0.00	5.50	83	26.5
Cyprus	33°00′E	35°00′N	0.93	0.11	12.28	498	18.9
Egypt	30°00′E	27°00′N	100.15	3.54	3.54	51	21.0
Eritrea	39°00′E	15°00′N	11.76	0.67	5.71	384	16.0
Ethiopia	38°00′E	08°00′N	110.43	14.51	13.14	848	16.6
Iran	53°00′E	32°00′N	174.52	18.77	10.76	228	16.7
Iraq	44°00′E	33°00′N	43.83	5.45	12.43	216	22.7
Jordan	36°00′E	31°00′N	8.88	0.23	2.60	111	17.3
Kuwait	45°45′E	29°30′N	1.78	0.02	0.84	121	25.6
Lebanon	35°50′E	33°50′N	1.05	0.29	27.24	661	20.6
Libya	17°00′E	25°00′N	175.95	2.05	1.17	56	20.4
Morocco	5°00′W	32°00′N	44.66	8.98	20.11	346	17.7
Oman	57°00′E	21°00′N	30.95	0.09	0.30	125	28.6
Qatar	51°15′E	25°30′N	1.16	0.02	1.38	74	27.1
Saudi Arabia	45°00′E	25°00′N	214.97	3.68	1.71	59	25.4
Sudan	30°00′E	15°00′N	250.58	20.91	8.34	416	29.2
Syria	38°00′E	35°00′N	18.52	5.67	30.59	252	17.0
Tunisia	9°00′E	34°00′N	16.36	5.04	30.81	207	17.7
Turkey	35°00′E	39°00′N	78.36	24.51	31.27	593	11.4
UAE	54°00′E	24°00′N	8.36	0.27	3.17	78	27.1
Yemen	48°00′E	15°00′N	52.80	1.61	3.04	167	29.2
Total	—	—	1584.22	124.83	7.88	—	—

Source: World Climate. 2011. http://www.worldclimate.com. Accessed September 15, 2011; TravelBlog. 2011. http://www.travelblog.org/World/ag-geog.html. Accessed September 21, 2011; Food and Agriculture Organization. Aquastat database query. 2011. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en. Accessed September 17, 2011.

[a] Location was obtained from TravelBlog (2011). Longitude and latitude represent the central point of each country.

[b] Total and cultivated area information and mean annual precipitation (MAP) were obtained from FAO (2011).

[c] Mean annual temperature was obtained from World Climate (2011).

are almost constant, but may decrease as a result of anthropogenic activities and/or climate change, which may alter the temperature and rainfall. By contrast, the total population of the region is rapidly increasing. Consequently, the demand for food is also increasing. The total population during the middle of the twentieth century was not an issue either in terms of food security or for other demands because both the water and land resources were adequate. Since 1950, however, the region has witnessed a drastic increase in the total population. Yet, the water and land resources are limited. Consequently, food security and water resources are among the major constraints. This imbalance between people and natural resources is receiving the attention of international organizations such as the United Nations (UN), the Food and Agriculture Organization (FAO), the World Bank, national/regional organizations such as the Arab Organization for Agricultural Development (AOAD), and the International Center for Agricultural Research in the Dry Areas (ICARDA). Food security is emerging as a major issue in the region.

This chapter focuses on water resources, both conventional and nonconventional, in view of the increasing demographic pressure, with a focus on soil water. The availability of water resources is addressed in terms of the water withdrawals of the agricultural, industrial, and municipal sectors. It also addresses per capita food availability, in general, and food security in Egypt as a specific case study.

7.2 THE REGION

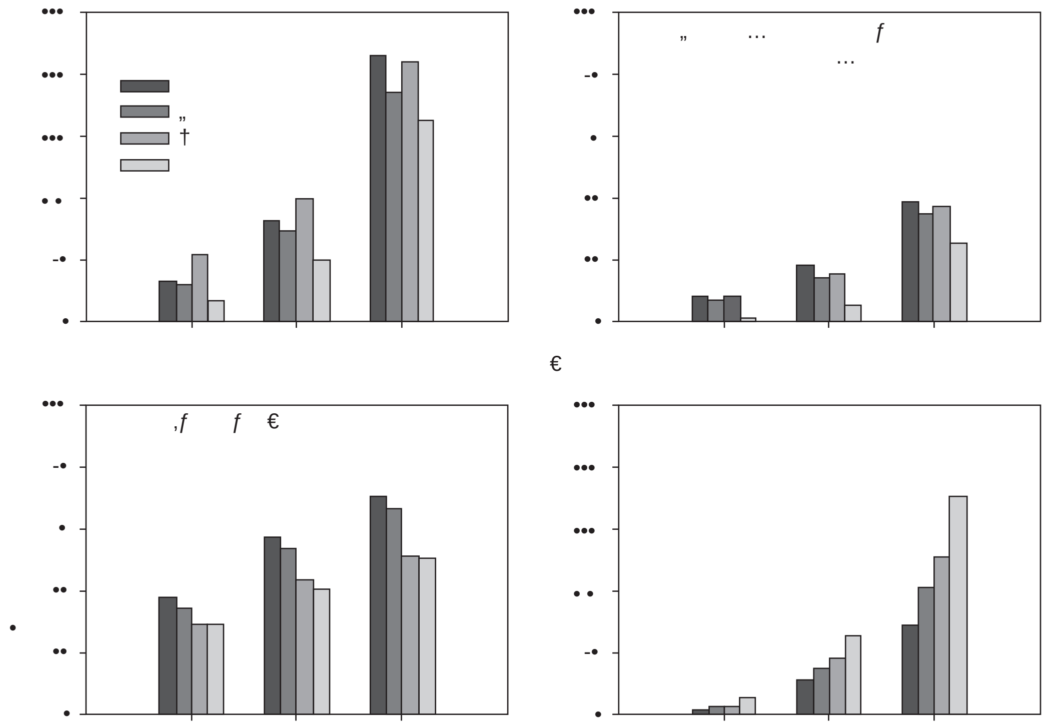
7.2.1 POPULATION

In the middle of the twentieth century, the total population of the region was 131.4 million inhabitants, which was 5.2% of the world's total population at that time (Table 7.2 and Figure 7.2). By 1960, this population had increased to 167.7 million at an average annual growth rate of 2.8%. Between 1960 and 1990, the annual rate of population growth in the region increased to 3.2% compared with a 2% growth rate in the world's population. Thus, the total population of the WANA region reached 378.3 million inhabitants in 1990 or 7.13% of the total world population (Table 7.2 and Figure 7.2). Shortly after the 1990 census, the governments of the region realized the problems associated with a high population (e.g., housing shortage, rising food prices, and lack of health facilities). Thus, several policy interventions were implemented to slow down the population growth. Consequently, by 2009, the growth rate had decreased from 3.2% to 2.2% and continues to decline (Figure 7.2). Therefore, the projected population will be 775 million (9.3% of the world's total population) by 2030, with an average growth rate of 1.4%, and 925 million (9.9% of the world's total population) by 2050, with an average annual growth rate of 0.8% (Table 7.2 and Figure 7.2).

TABLE 7.2
Total Population of the WANA Region between 1950 and 2050

	Total Population (Million Inhabitants)										
Country	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Algeria	8.8	10.8	13.8	18.8	25.3	30.5	35.5	40.2	43.5	45.5	46.5
Bahrain	0.1	0.2	0.2	0.4	0.5	0.6	1.3	1.5	1.7	1.8	1.8
Cyprus	0.5	0.6	0.6	0.7	0.8	0.9	1.1	1.2	1.3	1.3	1.3
Egypt	21.5	27.9	35.9	45.0	56.8	67.7	81.1	94.8	106.5	116.2	123.5
Eritrea	1.1	1.4	1.8	2.5	3.2	3.7	5.3	6.8	8.4	10.0	11.6
Ethiopia	18.4	22.6	29.0	35.4	48.3	65.6	83.0	101.0	118.5	133.5	145.2
Iran	17.4	22.0	28.7	38.6	54.9	65.3	74.0	81.0	84.4	85.9	85.3
Iraq	5.7	7.4	10.0	13.7	17.4	23.9	31.7	42.7	55.3	69.0	83.4
Jordan	0.5	0.9	1.7	2.3	3.4	4.8	6.2	7.4	8.4	9.3	9.9
Kuwait	0.2	0.3	0.8	1.4	2.1	1.9	2.7	3.4	4.0	4.6	5.2
Lebanon	1.4	1.9	2.5	2.8	3.0	3.7	4.2	4.5	4.7	4.8	4.7
Libya	1.0	1.4	2.0	3.1	4.3	5.2	6.4	7.1	7.8	8.4	8.8
Morocco	9.0	11.6	15.3	19.6	24.8	28.8	32.0	35.1	37.5	38.8	39.2
Oman	0.9	1.1	1.1	1.5	2.1	3.2	4.0	5.3	6.8	8.2	9.7
Qatar	0.0	0.1	0.1	0.2	0.5	0.6	1.8	2.2	2.4	2.5	2.6
Saudi Arabia	3.1	4.0	5.8	9.8	16.1	20.1	27.5	33.5	38.5	42.2	44.9
Sudan	9.2	11.6	14.8	20.1	26.5	34.2	43.6	54.9	66.9	79.1	91.0
Syria	3.4	4.6	6.4	8.9	12.3	16.0	20.4	24.1	27.9	30.9	33.1
Tunisia	3.5	4.2	5.1	6.5	8.2	9.5	10.5	11.5	12.2	12.5	12.7
Turkey	21.2	28.2	35.5	44.1	54.1	63.6	72.8	80.8	86.7	90.3	91.6
UAE	0.1	0.1	0.2	1.0	1.8	3.0	7.5	9.2	10.5	11.5	12.2
Yemen	4.3	5.1	6.2	8.0	12.0	17.7	24.1	32.2	41.3	51.3	61.6
Total	131.4	167.7	217.3	284.2	378.3	470.6	576.3	680.5	775.0	857.5	925.6
World	2532.2	3038.4	3696.2	4453.0	5306.4	6122.8	6895.9	7656.5	8321.4	8874.0	9306.1

Source: United Nations. Department of Economic and Social Affairs, Population Division, Population Estimates and Projections Section. World population prospects, the 2010 revision. 2010. http://esa.un.org/unpd/wpp/unpp/panel_population.htm. Accessed September 25, 2011.



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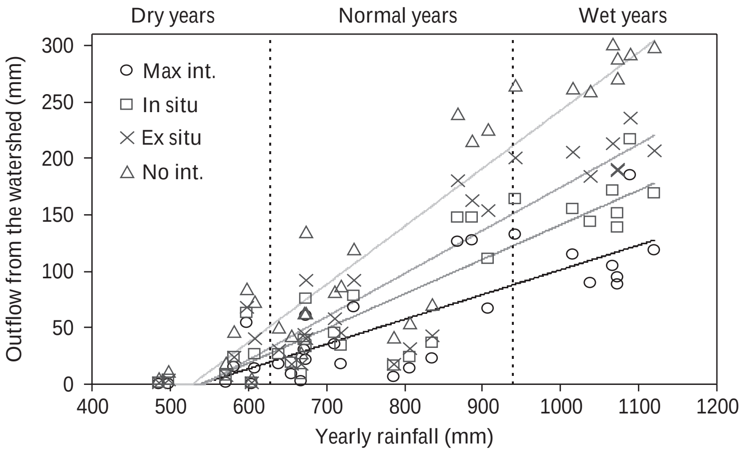

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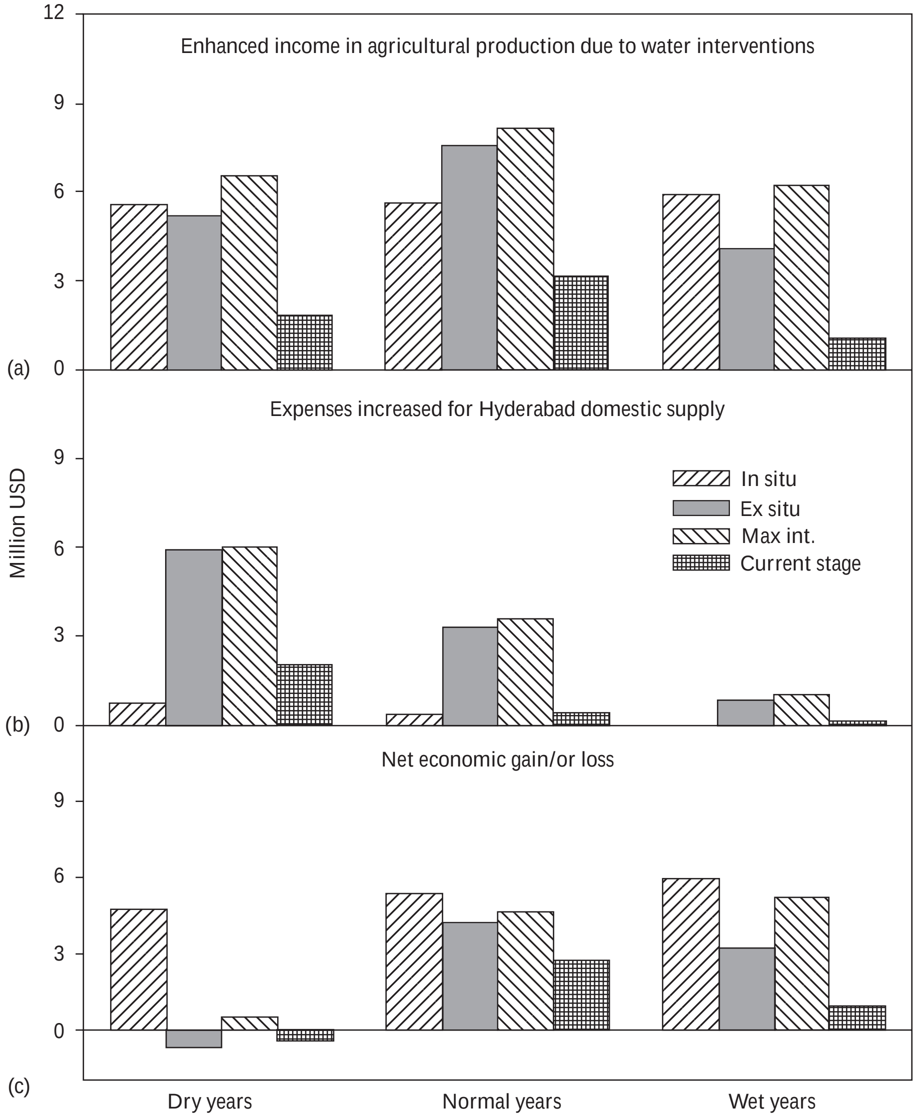
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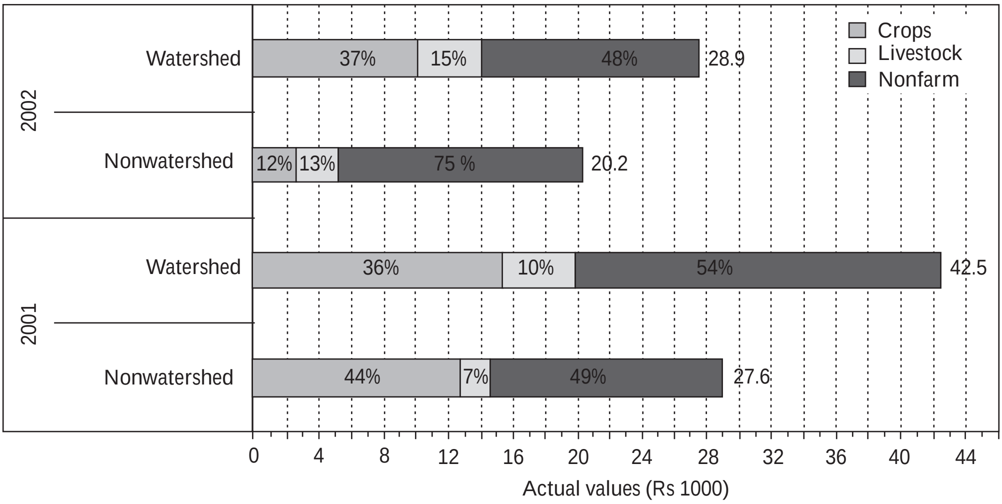
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14 Manipulating Crop Geometries to Increase Yields in Dryland Areas

B.A. Stewart and Rattan Lal

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14.1 INTRODUCTION

Drylands comprise regions characterized by different moisture regimes on the basis of the rainfall received. A region is termed hyperarid if the annual rainfall is <200 mm, arid if <200 mm during winter and <400 mm during summer, semiarid if 200–500 mm during winter and 400–600 mm during summer, and dry subhumid if 500–700 mm during winter and 600–800 mm during summer (FAO 1993). On the basis of the length of the growing season, considering favorable water balance and temperature regime, a region is categorized arid if the growing season is <75 days, semiarid if 75–120 days, and dry subhumid if 120–150 days (FAO 1993). These regions are also classified on the basis of the aridity index (AI), defined as the ratio of precipitation (P) to potential evapotranspiration (PET). The region is termed hyperarid if AI is <0.05, arid if 0.05–0.2, semiarid if 0.2–0.5, and dry subhumid if 0.5–0.65. Globally, these regions occupy 1.96 billion hectares (Bha) in Africa, 1.95 Bha in Asia, 0.66 Bha in Australasia, 0.3 Bha in Europe, 0.74 Bha in North America, and 0.54 Bha in South America (Table 14.1). Thus, drylands occupy a total of 6.15 Bha or 47.1% of the earth's land area. Principal soils consist of Aridisols (2.1 Bha), Entisols (2.3 Bha), and Alfisols (0.38 Bha) (Table 14.2). Most soils (except Vertisols and Mollisols) are coarse-textured and low in soil organic matter content and inherent soil fertility. Drought stress, low nutrient reserves, and susceptibility to erosion (by water and wind) and secondary salinization are principal soil-related constraints to achieving high biomass production and agronomic yields.

During the past 50 years, world cereal production increased about 2.7 times compared to 2.3 times for world population. This increased production was a remarkable achievement and the result of many factors. However, increased irrigated areas and increased use of chemical fertilizers are clearly two of the most important reasons. Irrigated areas more than doubled and fertilizer consumption increased several fold. Irrigated lands and favorable rainfed areas benefitted greatly

TABLE 14.1
Continental Distribution of the World's Drylands

	Area (Bha)					% of Earth's Land Area
Region	**Hyperarid**	**Arid**	**Semiarid**	**Dry Subarid**	**Total**	
Africa	0.67	0.5	0.51	0.27	1.96	15.0
Asia	0.28	0.63	0.69	0.35	1.95	14.9
Australasia	0	0.3	0.31	0.05	0.66	5.1
Europe	0	0.01	0.11	0.18	0.30	2.3
North America	0.003	0.08	0.42	0.23	0.74	5.6
South America	0.03	0.05	0.27	0.21	0.54	4.2
Total	0.98	1.57	2.31	0.30	6.15	
% of earth's area	7.5	12.0	17.7	9.9		47.1

Source: Adapted from Middleton, N.J. and Thomas, D.S.G., *World Atlas of Desertification*, Edward Arnold/UNEP, Seven Oaks, TN, 1992; Noin, D. and Clark, J.I., In: *Population and Environment in Arid Regions*, eds. J. Clark and D. Noin, MAB/UNESCO, Vol. 19, The Parthenon Publishing Group, New York, 1997; Food and Agriculture Organization, *Land Resource Potential and Constraints at Regional and Country Levels*, World Soil Resources Report 90, FAO, Rome, Italy, 2000.

Note: Bha = 10^9 ha = billion hectares.
Earth's total land area = 13.06 Bha.

from chemical fertilizers and also from improved plant cultivars that resulted from plant breeding and molecular biology. Rainfed areas are generally considered areas that are not irrigated but that receive enough precipitation to allow the cultivation of crops. The climates for these areas, however, are highly variable ranging from semiarid to humid. A lack of water limits the yield in nearly all climates unless irrigation water is added, but the extent of the limitation varies greatly. It can be anticipated in humid regions that there will be sufficient precipitation to avoid drought that

TABLE 14.2
Continental Distribution of Major Dryland Soils

	Area (Bha)							% of Earth's Land Area
Soil Order	**Africa**	**Asia**	**Australasia**	**North America**	**South America**	**Europe**	**Total**	
Alfisols	0.235	—	0.0464	0.0294	0.0706	?	0.3815	2.9
Aridisols	0.549	0.799	0.2917	0.3312	0.1520	?	2.1229	16.3
Entisols	1.136	0.663	0.2453	0.0589	0.2281	?	2.3313	17.9
Mollisols	0.0196	0.3898	—	0.3018	0.0923	?	0.8035	6.2
Vertisols	0.0169	0.0975	0.0796	0.0147	—	?	0.2087	1.6
Total	1.959	1.949	0.663	0.736	0.543	0.30	6.15	
% of earth's land area	15.0	14.9	5.1	5.6	4.2	2.30		47.1

Source: Recalculated from Dregne, H.E., *Soils of the Arid Regions*, Elsevier, Amsterdam, 1976; Noin, D. and Clark, J.I., In: *Population and Environment in Arid Regions*, eds. J. Clark and D. Noin, MAB/UNESCO, Vol. 19, The Parthenon Publishing Group, New York, 1997.

threatens the survival of a crop, but complete crop failure often occurs in semiarid regions. There are different approaches used for classifying climates, and Stewart et al. (2006) present and discuss some of these. Although rainfed areas include all of the cultivated areas that are not irrigated, many workers tend to separate rainfed areas into more favorable and less favorable areas. The less favored areas are commonly called dryland areas. Hargreaves (1957) defined dryland farming as agriculture without irrigation in regions of scanty precipitation. Stewart and Burnett (1987) stated that dryland farming emphasizes water conservation in every practice throughout the year. Bowden (1979) further divided semiarid lands into the semiarid tropics and the mid-latitude steppes. However, he listed four keys that are unique and that apply to all semiarid lands.

- *Key 1*: No growing season is or will be nearly the same in precipitation amount, kind, or range, or in temperature average, range, or extremes, as the previous growing season. Although this key is critical in any rainfed system, it requires absolute attention in dryland farming. Crop cultivation requires an adjustment every year, which leads to the second key.
- *Key 2*: Crops cannot be planned or managed to be the same from season to season. Most of the world's agricultural practices in either humid or arid areas have some predictability on an annual basis. In semiarid climates, however, even highly mechanized, technically advanced, commercial farms such as those in the High Plains of North America or the outback of Western Australia do not have sufficiently stable production for the individual or government to count on a given production figure for the following season.
- *Key 3*: The soil and water resource does not remain the same for any long period of time once agriculture is introduced into a semiarid region. A generalization necessary to support this key is that soils of most semiarid lands developed under grass on relatively flat topography. The competition for water and nutrients to produce crops requires removal of the protective grass cover. Because the crops are annual and dependent on precipitation, severe drought often leaves the soil highly vulnerable to wind erosion.
- *Key 4*: There is abundant sunshine due to many cloud-free days. This key has potential benefit and is shared with most arid climates. Abundant sunshine means higher temperatures that induce rapid growth, but it also creates a situation that demands careful management of soil water. Warm seasons, abundant sunshine, and cloud-free conditions stimulate growth but also increase evaporation and transpiration. It is possible for a grain crop to mature rapidly due to several weeks of sun-drenched, rainless conditions and desiccate just days before ripening. It is equally possible for a few millimeters of precipitation to occur at almost the last moment and produce a good crop.

14.2 EXAMPLE SEMIARID REGION

Dryland areas occur in many parts of the world. By the Food and Agriculture Organization (FAO) classification system that is based on the number of growing days (FAO 2000), 45% of the world's total land area is considered drylands. In this treatise, only the dryland area of the Central and Southern Great Plains of the United States will be discussed in detail, but the principles and technologies presented will be applicable to other areas. The similarities and differences of the climate in this area compared to other dryland regions of the world have been presented and discussed by others (Peterson et al. 2012, Chapter 16; Stewart 1988; Unger et al. 2006). Akron, CO, and Big Spring, TX, are the locations where USDA Agricultural Research Service has conducted experiments since the early 1900s. The average monthly PET values are much higher than the average monthly P values (Figure 14.1). In fact, there is not a single month in the year where the average P even reaches one-half of the PET value. The approximate location of these sites within the Great Plains is shown in Figure 14.2. While the entire Great Plains is considered semiarid, the degree of aridity increases moving from north to south because the temperature gradient increases in that direction, while the precipitation increases mostly from west to east. In general terms, the precipitation is about 400 mm

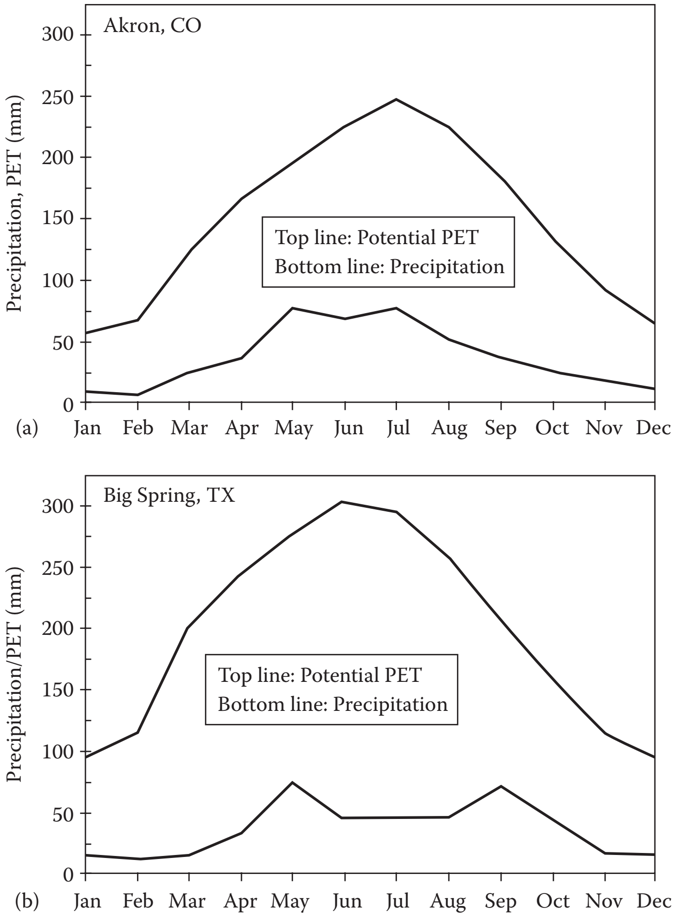


FIGURE 14.1 (a, b) Monthly average potential evapotranspiration (Penman–Monteith equation) and precipitation for two locations in the U.S. central and southern Great Plains (see Figure 14.2).

on the west side of the Great Plains and about 650 mm on the east side. The low precipitation amounts on the west side of the Great Plains and the high temperatures in the southern portions make these areas very close to arid. Therefore, dryland crop production generally requires fallowing the land for several months between crops to store sufficient water in the soil profile to supplement the growing season precipitation. Wheat (*Triticumaestivum* L.), grain sorghum (*Sorghum bicolor* (L.) Moench), and cotton (*Gossypiumhirsutum*) are the most widely grown dryland crops; maize (*Zea mays*) and sunflower (*Helianthus annuus*) are sometimes included in a cropping system.

The proportion of precipitation received during the fallow period stored in the soil profile for use by a subsequent crop was historically only 15%–20%. However, the use of limited and no-tillage systems has increased this significantly. Peterson et al. (2010, Chapter 16) have summarized some recent studies and have shown that 40% or more of the precipitation can be stored, and this has greatly increased the dryland crop production.

14.3 MANIPULATING CROP GEOMETRIES

Although a tremendous amount of research has been conducted during the past three or four decades on using crop residues to increase soil water storage, there has been little or none on manipulating crops to increase the efficiency of using this additional water. Loomis (1983) states that crop manipulations involve variations in the choice of species and cultivar, timing of events,

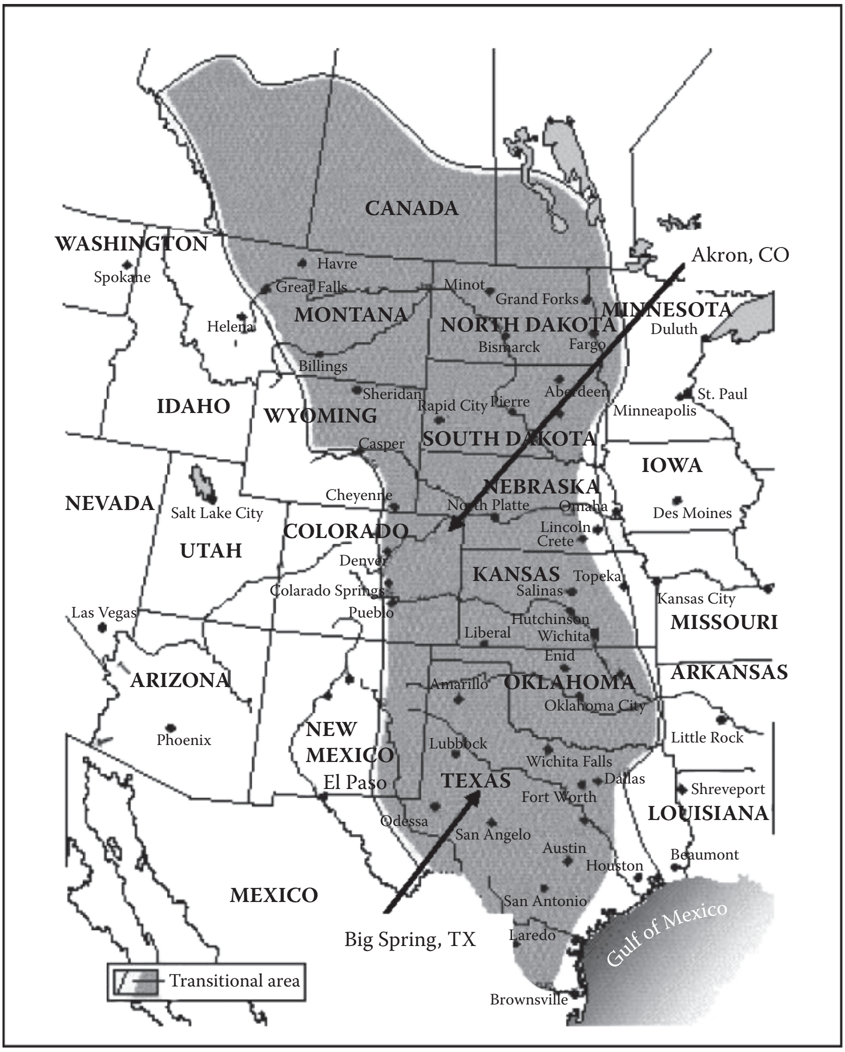

CANADA
WASHINGTON
Spokane
Havre
Great Falls
Minot
Grand Forks
MINNESOTA
Duluth
Akron, CO
Helena
MONTANA
NORTH DAKOTA
Bismarck
Fargo
Billings
Sheridan
St. Paul
Aberdeen
IDAHO
WYOMING
Rapid City
Pierre
Minneapolis
Casper
SOUTH DAKOTA
IOWA
NEBRASKA
Cheyenne
North Platte
Omaha
NEVADA
Salt Lake City
Des Moines
COLORADO
Lincoln
Crete
UTAH
Denver
KANSAS
Topeka
Salinas
Colorado Springs
Kansas City
Las Vegas
Pueblo
Hutchinson
Liberal
Wichita
MISSOURI
Enid
ARIZONA
Amarillo
OKLAHOMA
ARKANSAS
Oklahoma City
Phoenix
NEW MEXICO
Lubbock
Little Rock
Wichita Falls
El Paso
TEXAS
Dallas
Shreveport
Fort Worth
LOUISIANA
Odessa
San Angelo
Austin
Beaumont
Houston
MEXICO
San Antonio
Gulf of Mexico
Big Spring, TX
Laredo
Transitional area
Brownsville

FIGURE 14.2 The Great Plains of the United States and Canada (approximate locations of Big Spring, TX, and Akron, CO, are shown by the arrows).

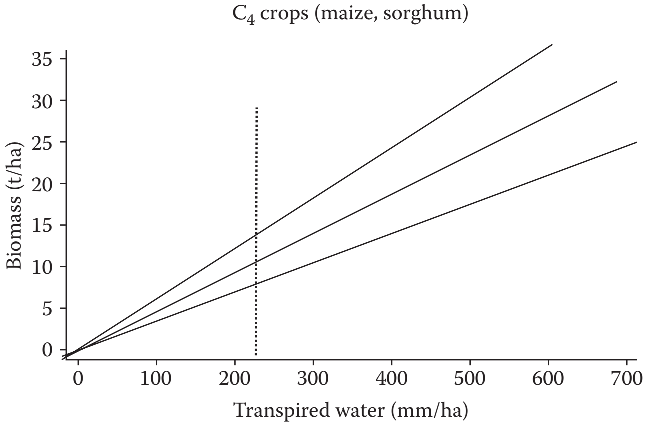
plant density, fertility status, provision for irrigation, and other factors. He emphasizes that where water is limiting, several basic strategies need to be followed to bring crops to maturity within the available supply: (1) ensure that a large proportion of the available water goes to transpiration, (2) achieve a high level of production per unit of transpiration, and (3) achieve a balance between seasonal use of water and seasonal supply. In principle, plant spacing can be varied in a way that influences the time when stored moisture is used. Roots can reach all of the soil mass earlier in the season with a regular spacing than with a clumped pattern. Where plants are closely spaced within rows (or hills), but widely spaced between rows, roots may reach the interrow soil mass much later in the season (Loomis 1983). Crop yields may or may not be increased by different arrangements depending on the stored soil water supply, time and amount of growing season precipitation, depth and lateral extent of rooting, and other factors. Loomis stated that a useful generalization is that where water is limiting, nonuniform treatment of the land or the crop can be an advantage, but where water is not limiting, uniform cropping will provide the greatest efficiency in light interception and photosynthesis.

In dryland areas such as described earlier, water is always limited. However, since dryland crops are commonly grown on land that has been fallowed for several months, there is generally considerable plant available water in the soil profile at the time of seeding. Careful management and well-designed strategies are necessary to prevent most or all of this water from being utilized for vegetative growth because this will almost certainly lead to a severe lack of water during the later growth stages that determine the quantity and quality of the yield. It is critical, particularly for grain crops, that plants have available water during the reproductive and grain-filling periods. Craufurd et al. (1993) reported that water stress during booting and flowering stages resulted in a grain yield reduction of up to 85%.

14.3.1 VAPOR PRESSURE DEFICIT EFFECT ON TRANSPIRATION

Plant growth is directly related to water availability (Sinclair 2009a). Sinclair states that the difference in vapor pressure inside and outside a leaf (VPD) is what controls the rate of water loss through the stomata. The VPD in arid regions is large because the vapor pressure in the atmosphere is low. For a given environment, the VPD cannot be controlled—it is what it is. Sinclair (2009b) stated that "Despite claims that crop yields will be substantially increased by the application of biotechnology, the physical linkage between growth and transpiration imposes a barrier that is not amenable to genetic alteration."

Sinclair and Weiss (2010) state that a C_4 crop growing in a 2 kPa transpiration environment will have a transpiration rate of approximately 220 g water/day for each gram of plant growth. By contrast, a C_3 crop will require 330 g water/day for each gram of plant growth. The water requirement, however, is greatly influenced by the climatic variables. The relationship between transpiration and biomass production for three different climates is shown in Figure 14.3. The amount of biomass produced from 400 mm water can be almost two times more for plants growing in a humid environment compared to an arid environment. The microclimate of plants, specifically the vapor pressure deficit, is determined by temperature, radiation, humidity, and wind, or in simple terms: (1) how hot it is, (2) how sunny it is, (3) how dry the air is, and (4) how windy it is. These characteristics are usually measured in the environment close to where plants are growing, but the vapor pressure deficit of the plant leaves is generally not measured. Therefore, an important link is generally missed. It is the vapor pressure deficit of the plant leaves that determines the transpiration rate—not the surrounding environment. Even though these may be somewhat similar, the plants often grow in a microclimate



Top line: Humid climate, 1.5 kPa VPD, 160 g transpiration for 1 g biomass
Middle line: "Average" climate, 2.0 kPa VPD, 220 g transpiration for 1 g biomass
Bottom line: Arid climate, 2.5 kPa VPD, 280 g transpiration for 1 g biomass

FIGURE 14.3 The effect of different climates on the amount of water transpired for each gram of above ground biomass produced. (Figure based on information from Sinclair, T.R. and Weiss, A., *Principles of Ecology in Plant Production*, 2nd edn, CAB International, Cambridge, MA, 2010.)

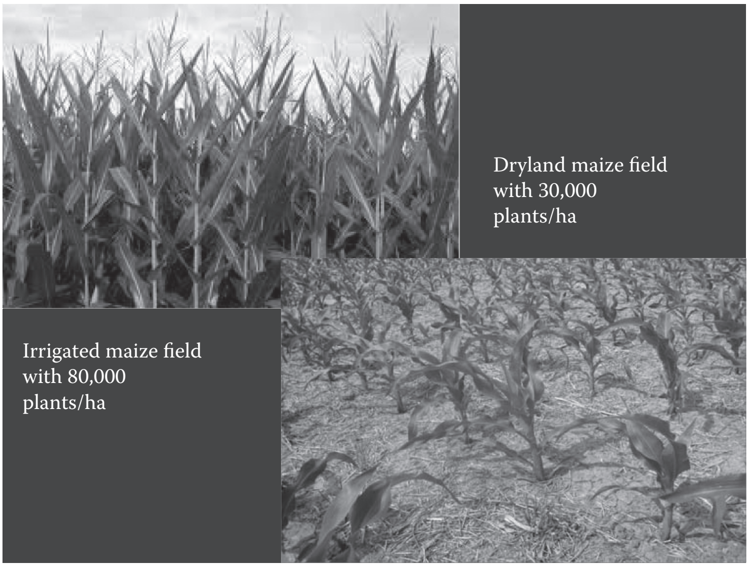


FIGURE 14.4 Maize plants growing in very different microclimates but in the same general environment.

that is significantly different from the surrounding environment. Figure 14.4 shows two fields of maize very close to each other, but the microclimate is very different for the plants in the different fields. Even if the plants are genetically the same, the transpiration efficiency will differ because the temperature, radiation, humidity, and wind speed will be different at the leaf surface.

Historically, plants were often grown in clumps, or hills, where there would be several plants close together and then open space between the clumps. William Brown, who later became the President of Pioneer Hi-Bred International, Inc., investigated during the mid-1950s the origin, evolution, and culture of some of the important crops that furnish the major sources of food for certain native Americans of the desert area of southwestern United States (Brown 1985). In parts of what are now Arizona and New Mexico, a number of Indian tribes and their ancestors learned and practiced the art of dryland agriculture with a high degree of success. The way maize was grown would not be recognized in most areas today, but it was based on methods that had sustained their needs for centuries. Some is still being grown similarly today in areas using seed that has been naturally selected over many years. The corn is planted in hills about 2 m apart, and the hills are in rows, also equally widely spaced (Figure 14.5). A hill contains 10–12 or even more plants. The Indians learned that the clumping of plants within a relatively small space reduces the desiccation of the foliage, anthers, and silk that allows normal fertilization to occur in an extremely arid environment. Singularly spaced plants growing in the same environment seldom produce an ear.

Recent studies (Bandaru et al. 2006; Kapanigowda et al. 2010; Krishnareddy et al. 2010) have shown the cultivation of grain sorghum and maize plants in clumps compared to equally spaced geometries. For each crop, the number of plants m^2 was equal. Bandaru et al. (2006) grew grain sorghum under semiarid conditions at Bushland, TX, and Tribune, KS, in clumps of either three or four plants and compared vegetative growth, tillering, harvest index, and grain yield to plants uniformly spaced. A schematic showing the treatments in this study is presented in Figure 14.6, and the results from the experiments conducted in 2004 on the no-tilled study area at Bushland are presented in Table 14.3. Bandaru et al. (2006) concluded that growing plants in clumps compared to uniformly spaced plants reduces the number of tillers and vegetative growth. This preserves the soil water until reproductive and grain-filling growth stages, which increases the grain yield. There are marked differences in the plant architecture of uniformly spaced plants compared to clumped plants. Uniformly spaced plants produce more tillers, and the leaves on both the main stalk and

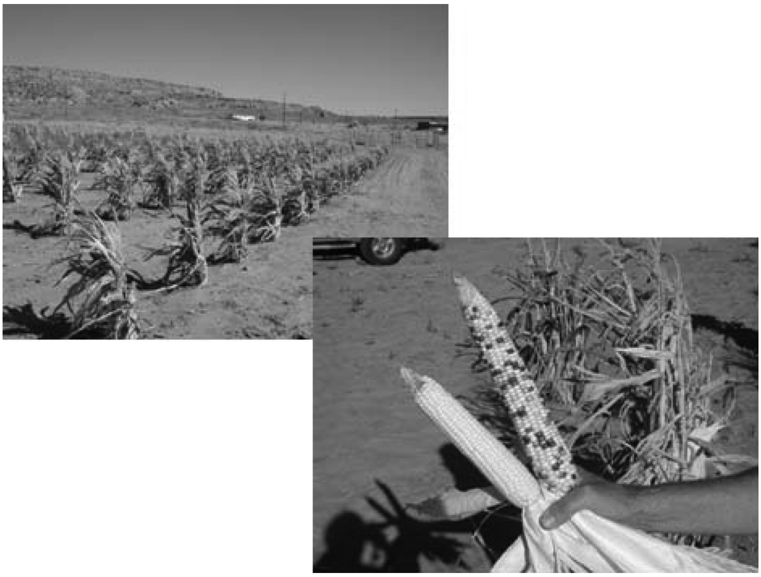


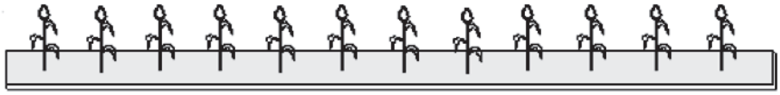
FIGURE 14.5 Dryland maize in 2005 growing on the Hopi Indian Reservation in Arizona in an arid environment.

the tillers grow outward, exposing essentially all of the leaf area to sunlight and wind. By contrast, clumped plants grow upward with the leaves partially shading on another and reducing the effect of wind, thereby reducing water use. The benefit of clumps decreased as grain yields increased, and there was even a slight decrease when yields exceeded 6000 kg/ha. However, grain yields were increased by clump planting by as much as 100% when yields were in the 1000 kg/ha range and 25%–50% in the 2000–3000 kg/ha range.

Kapanigowda et al. (2010) grew maize under dryland conditions at Bushland, TX, and also when small amounts (50–125 mm) of seasonal irrigation water were added. Two planting geometries, clumps of three plants 1 m apart and equidistant-spaced plants in 75 cm rows, were compared at plant populations of 39,000 plants/ha. Clump planting produced significantly greater grain yields (321 vs. 225 g/m^2 and 454 vs. 292 g/m^2 during 2006 and 2007, respectively) and harvest indexes (0.54 vs. 0.49 and 0.52 vs. 0.39 during 2006 and 2007, respectively) compared with equidistant plants under dryland conditions. Water-use efficiency measurements in 2007 indicated that clumps had a lower evapotranspiration (ET) threshold for initiating grain production. The authors also concluded that mutual shading may have played a role in reducing transpiration and plants growing close to each other could have possibly reduced the effect of wind and lowered transpiration rates. Tillers, which will be discussed later, also played a part. Although maize does not produce nearly as many tillers as grain sorghum, tillers are often formed on maize plants when population density is low as is often the case in dryland conditions. Kapanigowda et al. (2010) found in 2007 that tillers accounted for 10% of the stover produced by equidistant-spaced maize plants, but less than 3% of the grain.

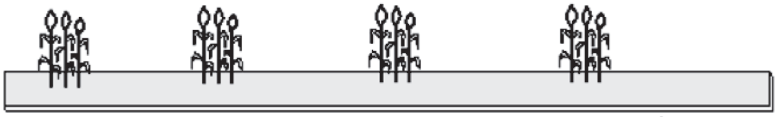
Recent unpublished data (MS theses in 2010 by Bharath Reddy and Brijesh Angira, West Texas A&M University, Canyon, TX) also support the hypothesis that plants growing in close proximity to one another change the microclimate enough to significantly affect the transpiration rate of maize and grain sorghum. Reddy grew grain sorghum and Angira grew maize, but the studies were conducted simultaneously in the same greenhouse, so the environmental conditions were the same. Reddy grew six grain sorghum plants in 1 m long boxes containing 93 kg soil (dry weight) maintained at two different water levels (soil water maintained between 75% and 100% plant available water and between 25% and 75% plant available water). The six plants in each box were arranged

Treatment SP-25



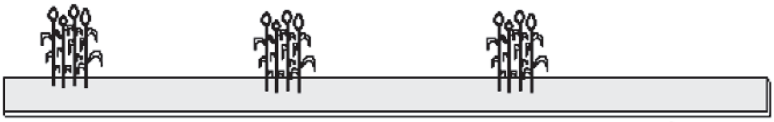
Single plants every 25 cm in 75 cm rows (5.4 plants/m^2)

Treatment C3-75



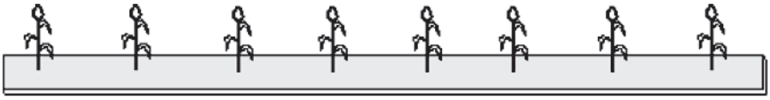
Three plants per clump every 75 cm in 75 cm rows (5.4 plants/m^2)

Treatment C4-100



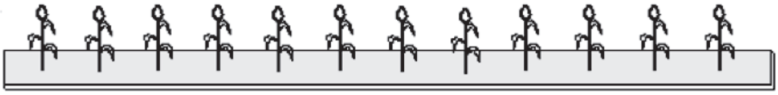
Four plants per clumph every 100 cm in 75 cm rows (5.4 plants/m^2)

Treatment SP-38



Single plants every 38 cm in 75 cm rows (3.6 plants/m^2)

Treatment SP-25-TR



Single plants every 25 cm in 75 cm rows (5.4 plants/m^2)
Tillers removed by hand when formed

FIGURE 14.6 A schematic showing plant geometries for growing grain sorghum under dryland conditions at Bushland, TX, and Tribune, KS. (From Bandaru, V., Stewart, B.A., Baumhardt, R.L., Ambati, S., Robinson, C.A., and Schlegel, A., *Agron. J.*, 98, 1109–1120, 2006.)

in three different geometries—two clumps of three plants with 50 cm between the clumps, six plants spaced 16.7 cm apart, and six plants spaced 8.4 cm apart. The center of the box was halfway between the clumps, and between the thirdplant and the fourthplant for the other two geometries. For the maize plants, Angira grew three plants in each box, and the three geometries were as follows: a clump with three plants, three plants 17 cm apart, and three plants 33 cm apart with the middle plant in all geometries located in the center of the box. Water levels were maintained at the same levels as for the maize study. All boxes were covered with lids that fit around the plants but were in two parts secured by bungee straps that could be removed for adding water, but they essentially eliminated evaporation, so the total water use was considered transpiration. Figure 14.7 shows all results from the two studies as a relationship between water transpired and aboveground biomass produced. Maize and grain sorghum are both C_4 crops, and as discussed earlier, Sinclair and Weiss (2010) stated that the transpiration ratio was constant for C_4 crops and was 220 g water for each gram of plant growth. The data presented in Figure 14.7 show that maize and grain sorghum had essentially the same ratios, and the ratios were almost the same regardless of whether the plants were grown under adequate water or limited water conditions. The values shown in Figure 14.7 were only the total biomass. There were large differences in the grain, and the maize plants produced

TABLE 14.3

Mean Values of Measurements for Grain Sorghum as Affected by Five Planting Geometries in 75 cm Rows in Experiments Located on the Upper (Upper), Middle (Middle), and Bench (Bench) Positions of a No-Tilled Bench-Terraced Field at Bushland, TX, in 2004[a]

Planting Geometry[b]	Tillers per Plant 28 DAP[c] (no. per plant)	Biomass 42 DAP (kg/ha)	Leaf Area Index Values 42 DAP	Panicles per m^2 (no. per m^2)	% Tillers with Panicles[d]	Grain (kg/ha)	Harvest Index Values	Aboveground Biomass (kg/ha)
Upper								
SP-25	2.2a[e]	2716a	1.30a	9.2a	33	2270b	0.29c	6866ab
C3-75	0.5c	1831c	1.10b	8.3b	106	2891a	0.38a	6673b
C4-100	0.5c	1622d	0.86c	7.7b	78	3011a	0.40a	6603b
SP-38	2.6b	2234b	1.29a	9.2a	61	2742a	0.33b	7288a
SP-25-TR	Removed	1550d	0.85c	5.4c	NA	2645ab	0.40a	5800c
Middle								
SP-25	2.3a	2924a	1.40a	10.3a	41	2690a	0.32a	7374ab
C3-75	0.7c	1897c	1.11c	9.7b	84	3338ab	0.40a	7320ab
C4-100	0.6c	1754d	0.90d	8.4b	103	3479a	0.42a	7266b
SP-38	2.7a	2352b	1.37b	10.3a	70	2954bc	0.33b	7852a
SP-25-TR	Removed	1634c	0.88d	5.4c	NA	2904c	0.39a	6561c
Bench								
SP-25	2.3a	3047a	1.45a	11.4a	50	4812a	0.41b	10295a
C3-75	0.9c	2088c	1.20c	9.1b	75	4968a	0.46a	9474b
C4-100	0.8c	1880d	0.93d	8.7b	84	4807a	0.46a	9167b
SP-38	2.8b	2478b	1.42b	11.5a	80	5070a	0.42b	10588a
SP-25-TR	Removed	1786d	0.92d	5.4c	NA	4222b	0.46a	8051c

Source: Bandaru, V., Stewart, B.A., Baumhardt, R.L., Ambati, S., Robinson, C.A., and Schlegel, A., *Agron. J.*, 98, 1109–1120, 2006.

[a] Separate but identical experiments were conducted on three positions that had different amounts of stored water at the time of seeding and different amounts of runoff or run-on during the cropping season.

[b] Planting geometries were SP-25 (plants ever 25 cm), C_3-75 (clumps of three plants every 75 cm), C_4-100 (clumps of four plants every 100 cm), SP-38 (plants every 38 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75 cm rows.

[c] Days after planting.

[d] Percentages were obtained by dividing the number of plants plus the number of tillers; values about 100 are due to an experimental error.

[e] Means in columns for a position on the benched terrace followed by the same letter are not significantly different according to a protected LSD mean separation ($P < 0.5$ level); each position represents a separate experiment and cannot be compared statistically.

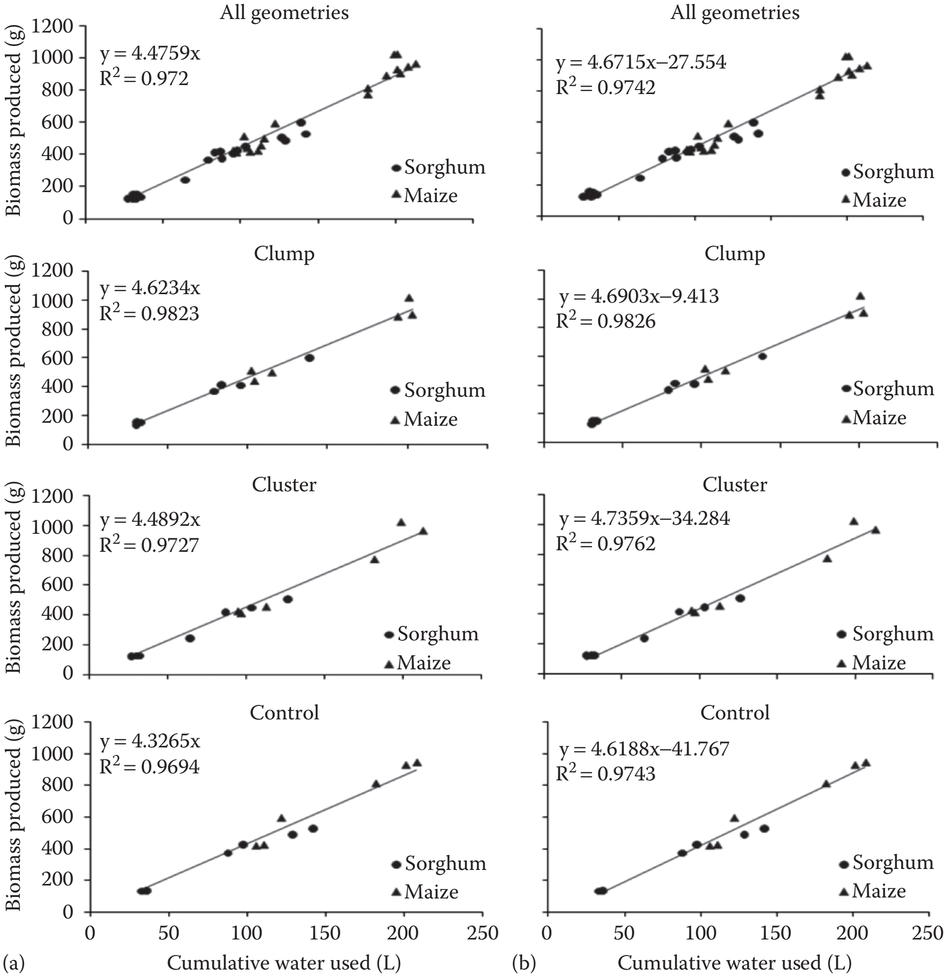


FIGURE 14.7 Grams aboveground biomass (y axis) as a function of liters water transpired (x axis) for maize and sorghum for all geometries and for different geometries; when line is statistically forced (b) and not forced (a) through the origin. (Figure based on the unpublished data of Reddy 2010 and Angira 2010.)

very little or no grain at the low water levels. The biomass, however, was directly proportional to water use as hypothesized earlier by Sinclair and Weiss (2010) in Figure 14.3.

The plants shown in Figure 14.8 under field conditions are in similar configurations to the maize plants grown in the greenhouse study presented above. The microclimate for the plants growing in clumps shown in the bottom half of the figure is likely to be more favorable during much of the time than that for the equally spaced plants shown in the top half, which should increase the transpiration efficiency.

14.3.2 PLANT SPACING EFFECT ON THE NUMBER OF TILLERS

Under dryland conditions, the most widely adopted strategy for growing grain crops such as maize and grain sorghum is to reduce the plant density. In irrigated areas and favorable precipitation regions, 80,000–90,000 plants/ha for maize and 200,000–250,000 plants/ha for grain sorghum are common. In dryland areas, the densities are often reduced by as much as 75%. Tiller numbers

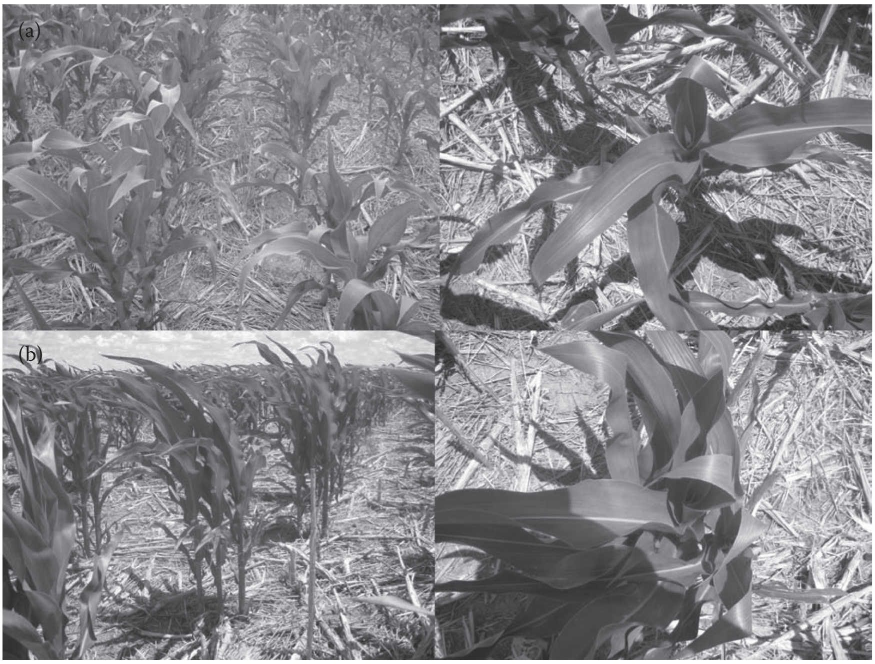


FIGURE 14.8 Maize plants growing in a farmer's field in clumps (b) compared to equally spaced plants (a) at populations of 30,000 plants/ha.

for plants, particularly for grain sorghum, increase with decreasing plant densities, and this often negates most if not all of the anticipated benefit. The purpose of decreasing plant population is to decrease the amount of stored soil water used for vegetative growth so that there is more of it remaining for use during the grain-filling period. The tillers use water and nutrients (Figure 14.9), but under water-limiting conditions, they often produce little or no grain. Gerik and Neely (1987), Bandaru et al. (2006), Kapanigowda et al. (2010), and Krishnareddy et al. (2010) have clearly shown that maize and grain sorghum plants produce significantly more tillers at low plant densities than at high densities. Although tillers can contribute to grain yields under some conditions, they are more likely to decrease yields under severe water-stressed conditions because the tillers often senesce before they produce the number of leaves required before a panicle is formed. The tiller data shown in Table 14.3 for grain sorghum show that two to three tillers were common for each plant when plants were spaced 25–38 cm apart. Plants in clumps produced on average less than one tiller per plant. This greatly affected the harvest index values and was believed to be the primary reason for the higher grain yields produced by the plants grown in clumps. However, a more favorable microclimate in the clumps may have also contributed to the yield increase.

14.3.3 EFFECT OF PLANT GEOMETRY ON SOIL WATER EXTRACTION

Aside from reducing plant populations, different spacing between rows and skip-row configurations have been widely used to enhance soil water contents later in the season. The most common spacing between rows of crops such as maize and grain sorghum is 75 cm, but 100 cm spacing between rows is often used in dryland areas. Configurations such as plant 1-skip 1, plant 2-skip 1, and plant 2-skip 2 are sometimes used, and this results in wide spacing between some rows (Lyon et al. 2009; Routley et al. 2003). Routley et al. (2003) found more consistent yields of grain sorghum in Australia when every third row or two rows of every four rows were left blank compared with uniformly spaced 1 m rows when yields were 2500 kg/ha or less. Yields were generally less for skip-row configurations at

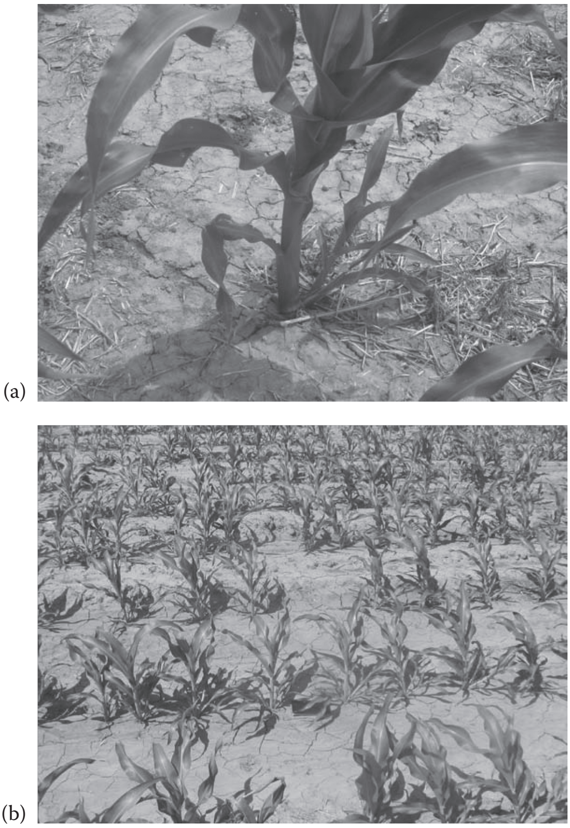


FIGURE 14.9 Maize (a) and grain sorghum (b) plants in farmer fields showing the formation of tillers when low plant populations are used.

higher yield levels. Lyon et al. (2009) grew maize at a number of locations for multiple years where annual precipitation amounts varied widely and compared yields for every 75 cm row planted to those of skip-row configurations of plant 2-skip 2, plant 2-skip1, and plant 1-skip 1. In trials where skip-row planting resulted in increased grain yields, the mean yield for the every-row treatment was 2800 kg/ha. In those trials where skip-row planting resulted in lower yields than the standard planting treatment, the mean yield was 8500 kg/ha.

Balancing soil water extraction with crop management is challenging. In general, stored soil water is more fully utilized by either closer row spacing or higher plant populations. The data in Table 14.4 clearly show that either increasing the plant density or decreasing the width between rows resulted in increased soil water extraction by grain sorghum, and this was particularly true between times of emergence and heading. The challenge is to try and save some of the stored water for the reproductive and grain-filling growth stages, and the data show that this can be done by wide rows or low population, but then much of the potential gain was lost because the water was not fully extracted. When most of the soil water is depleted during vegetative growth, the harvest index can be significantly reduced, resulting in low grain yields (Table 14.4). Finding the right balance is difficult because the amounts and distribution of precipitation in dryland regions are significantly different for every growing season.

Bandaru et al. (2006) showed that growing grain sorghum in clumps as illustrated in Figure 14.6 resulted in significantly less use of stored soil water early in the season as compared to equally spaced plants in rows. The differences at the end of the growing season were much smaller, but the equally spaced plants still used slightly higher amounts of soil water than the clump treatments (Table 14.5).

TABLE 14.4
Effect of Plant Population and Row Spacing on Dry Matter Yield, Harvest Index, and Deep (>0.9 m) and Shallow (<0.9 m) Soil Water Extraction by Grain Sorghum at Bushland, TX, in 1983

	Total Dry Matter	Harvest	Soil Water Extraction								
			Emergence to Heading (mm)			Heading to Maturity (mm)			Total Season (mm)		
	(Mg/ha)	Index	≤0.9 m	>0.9 m	Total	≤0.9 m	>0.9 m	Total	≤0.9 m	>0.9 m	Total
38[a]	5.3	0.38	75	11	86	30	19	49	105	30	135
76L	5.7	0.45	59	9	68	44	11	55	103	20	123
38M	6.4	0.39	85	15	100	27	21	48	112	36	148
76M	6.1	0.34	67	14	81	46	6	52	113	20	133
38H	6.2	0.25	98	17	115	28	14	42	126	31	157
76H	6.0	0.28	73	7	80	37	17	54	110	24	134

Source: Stewart, B.A. and Steiner, J.L., In: *Dryland Agriculture: Strategies for Sustainability*, eds. R.P. Singh, J.F. Parr, and B.A. Stewart, Advances Soil Science, vol. 13, pp. 151–173, 1990.

[a] L, M, H = low, medium, and high plant populations corresponding to 6.9, 13.1, and 18.6 plants/m^2, respectively; 38 and 76 represent 0.38- and 0.76 m spacing between rows, respectively.

TABLE 14.5
Total Soil Water (mm) in 180 cm Soil Profiles of Selected Treatments[a] at Various Times at Bushland, TX, in 2004

Position on Bench Terrace	29 July	18 August	14 September	4 October
Upper				
SP-25 (13 cm from plant)	474b[b]	429c	408c	487b
C4-100 (13 cm from clump)	532a	535bc	421bc	500ab
C4-100 (38 cm from clump)	530a	486a	453a	501ab
SP-25-TR (13 cm from plant)	634a	478ab	446ab	511ab
Middle				
SP-25 (13 cm from plant)	498b	447b	422b	499a
C4-100 (13 cm from clump)	558a	497a	453a	492a
C4-100 (38 cm from clump)	541a	506a	465a	493a
SP-25-TR (13 cm from plant)	552a	518a	480a	486a
Bench				
SP-25 (13 cm from plant)	548b	518b	481a	498a
C4-100 (13 cm from clump)	559a	545ab	492a	513ab
C4-100 (38 cm from clump)	541a	506ab	165a	493b
SP-25-TR (13 cm from plant)	552a	518a	480a	486a

Source: Bandaru, V., Stewart, B.A., Baumhardt, R.L., Ambati, S., Robinson, C.A., and Schlegel, A., *Agron. J.*, 98, 1109–1120, 2006.

[a] Treatments were SP-25 (plants every 25 cm), C4-100 (clumps of four plants every 100 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75 cm rows.

[b] Numbers followed by the same letter within a column for a particular position are not significantly different according to a protected LSD mean separation ($P < 0.05$ level).

14.4 IMPLEMENTING COMPLEMENTARY TECHNOLOGIES IN DRYLAND AREAS

Successful crop production in dryland areas requires careful management, and every practice must be assessed in terms of how it affects precipitation capture, retention, and use because water is always the most limiting factor. This chapter focuses on the use of precipitation and stored soil water during the growing season to maximize the grain production of grain sorghum and maize. A strategy that includes multiple technologies is essential, and it must be fully understood that results from year to year will vary because the amount and timing of growing season precipitation are highly variable, and this affects technologies in different manners. However, a good understanding of basic principles of water management can greatly improve the sustainable crop production.

Grain yield is determined by multiplying the harvest index value times the amount of aboveground biomass, and the aboveground biomass for a given crop is directly proportional to the amount of transpiration that is affected by the vapor pressure deficit. While these principles apply to all soils and climates, the results are vastly different. Crop water use during a growing season is generally considered ET, which is the sum of the water evaporated from the soil surface and that transpired through the leaves between the date of planting and harvest. Dryland areas have less seasonal precipitation but require more transpiration to produce a unit of dry matter, and evaporation potential is also higher for water loss from the soil. It was discussed earlier that a crop can require almost two times more water in an arid climate to produce a unit of dry matter compared to a humid region. Therefore, practices and priorities for practices can differ greatly for different regions.

The first priority for growing a crop in a dryland region is to maximize water use. For dryland conditions, this is the sum of growing season precipitation and the amount of stored soil water used by the crop. Runoff should be minimized, and it is highly important to utilize as much of the stored soil water as feasible because it can greatly increase the yield, and in some areas such as the U.S. Great Plains, an entire growing season is sacrificed to increase the amount of water stored in the soil at the time of planting because growing season precipitation alone is not sufficient. Therefore, it is important to utilize this water.

The second priority is to utilize practices that proportion as much of the ET to T as feasible. This is difficult in dryland areas because not only is there less ET, but the evaporation potential is greater. The best strategies for decreasing the evaporation are to increase canopy cover to increase shading and to use mulch. Again, both of these strategies are difficult in dryland areas because reduced plant populations provide less ground cover, and there are often not enough crop residues to provide good ground cover even if no tillage is used. In many dryland regions, the situation is even worsened by the removal of crop residues for animal feed or household fuel.

The third priority is to utilize practices that can possibly increase transpiration efficiency but not reduce transpiration. Biomass production is tightly linked to transpiration, and the biochemistry of photosynthesis has not been improved genetically (Blum 2009). The effective use of water and not water-use efficiency should be emphasized for improving crop production under drought stress, and the effective use of water implies maximal soil moisture capture for transpiration, which also involves reduced nonstomatal transpiration and minimal water loss by soil evaporation (Blum 2009). Transpiration efficiency is dependent on the crop species, but environmental conditions determine the vapor pressure deficit that controls the amount of water required to produce a unit of dry matter. The transpiration environment is determined by air temperature, radiation, humidity, and wind speed. However, the environment surrounding a plant leaf may be considerably different than the environment in general. Growing plants in clumps may offer some potential for improving the microclimate, which will in turn increase the transpiration efficiency. It is conceivable that some of the benefit obtained by growing crops in skip-row configurations where plant populations are kept constant is that the space between plants is reduced by 50%, which may result in a more favorable microclimate. The closer spacing of plants also reduces the formation of tillers that can utilize water and nutrients but contribute little or no grain under water-stressed conditions. Lyon et al. (2009) recommended for maize growers in the U.S. central Great Plains with moderate riskaversion and likely yield levels of about 6 Mg or less to plant one row and skip one row but keep the plant population the same as if every row was planted. As discussed earlier, they attributed the increased yield to having more stored soil water available for use during the grain-filling period, but it is conceivable that the closer spacing of plants also resulted in a more favorable transpiration environment. Another potential benefit of using clump geometry or a skip-row configuration is that fertilizer use efficiency may be enhanced. Nutrient uptake could possibly be higher if a fertilizer was applied only to the soil adjacent to the clumps or only in the planted rows in skip-row configurations.

The harvest index is also of great importance and is affected by all of the priorities discussed. The harvest index is genetically controlled; it is maximum only when water is adequate to minimize stress. Under dryland conditions, water is always limited, so the harvest index values seldom approach the maximum values. Prihar and Stewart (1990) estimated the genetic harvest index for grain sorghum and maize to be approximately 0.55 and 0.60, respectively. The harvest index values can decline significantly when water is severely limited during the grain-filling period. Under extreme conditions, the harvest index can be zero, particularly for maize.

14.5 CONCLUSION

The importance of dryland agriculture production continues to increase because of the increasing world population, increasing prosperity that results in diet changes that demand more grain, decreasing rate of irrigated land expansion, urban sprawl taking agricultural land out of production, and other factors. During the last few decades, the most significant change in dryland agriculture has been to reduce tillage. In many cases, tillage has been essentially eliminated, and this has resulted in an increase in the amount of the scarce precipitation that is used for ET that has increased yields. While the basic principles are generally well understood, the implementation of these is difficult because the amount of growing season precipitation in dryland regions is always insufficient and the timing of the scarce precipitation is highly variable, and this affects different management practices in different ways. Thus, a practice that increases yield 1 year can actually decrease yield in another year because of the timing of rainfall events. This chapter has focused on manipulating plant geometries to increase water-use efficiency and yield. It is well established that the amount of water required to produce a unit of dry matter is highly dependent on the environment, which is primarily controlled by temperature, radiation, humidity, and wind speed, and these characteristics are widely measured and reported. However, it is the vapor pressure deficit at the leaf surface rather than the field environment that controls the transpiration ratio. While these are similar, there is evidence that the microclimate of the plants can be affected by practices such as row spacing, clump planting, skip-row configuration, spacing between plants, and other plant manipulation schemes. Additional studies are needed to determine the feasibility and reliability of such technologies for increasing yields in dryland areas.

ABBREVIATIONS

ET	Evapotranspiration
FAO	Food and Agriculture Organization
VPD	Vapor pressure inside and outside a leaf

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15 Mulch Tillage for Conserving Soil Water

Paul W. Unger, R. Louis Baumhardt, and Francisco J. Arriaga

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15.1 INTRODUCTION

Mulching, that is, the practice of maintaining organic or inorganic materials on or applying them to the soil surface, is an ancient practice (Jacks et al. 1955; Lal 2006). Jacks et al. (1955), for example, stated that the practice of applying mulches to soil is possibly as old as agriculture itself. They mentioned that the ancient Romans placed stones on soils to conserve water and the Chinese used pebbles from the streambed for the same purpose. It is, indeed, well known that mulches provide water and soil conservation benefits. They maintain or improve the soil resource base and provide conditions for favorable plant growth and, from an agricultural viewpoint, satisfactory or enhanced crop productivity. In addition to providing for water and soil conservation, properly managed mulches provide soil temperature moderation; soil structure improvement; soil nutrient effects; and soil salinity, crop quality, and weed control (Unger 1995). The combination of these benefits, therefore, is highly important for achieving adequate food production for the ever-increasing human population.

A wide variety of materials are used as mulches, which may be organic or inorganic in nature (Unger 1995; Lal 2006). Mulching materials include crop residues, plant leaves and clippings, tree bark, manure, paper, plastic films, petroleum products, gravel, coal, and other materials. Crop residues are the main mulching materials under widespread agricultural conditions, but plastic mulches are also widely used in some countries and for some specialty crops.

The importance of conserving water for agricultural purposes has been recognized for centuries. Bennett (1939) cited numerous practices from ancient times that had water conservation benefits, even though they were used for other water-related purposes. In modern times, water conservation has become highly important because of the increasing competition for fresh water among nations, geographical regions, and segments of society that include agricultural, urban, industrial, and recreational users (Unger and Howell 1999).

Water for agriculture is derived from precipitation and also from streams, reservoirs, or aquifers where crops are irrigated. Precipitation may be limited or erratic and supplies in streams, reservoirs, or aquifers may be limited or declining. Water conservation for agriculture, therefore, is important because of the limited supplies, increasing competition for available water supplies, and the need for increased food, fiber, and fuel production for the ever-increasing world population. For this report, we emphasize mainly the use of tillage to manage crop residues and other organic materials (e.g., cover crops) as a mulch to conserve soil water.

15.2 TILLAGE METHODS/SYSTEMS

Mulch tillage is tillage or soil preparation that retains plant residues or other materials to cover the soil surface. Operationally, it is any full-width tillage and planting combination that results in at least 30% of the soil surface covered with crop residues (SSSA 2001). Because of the wide array of crops grown, amounts of residue produced, residues used for other purposes, soils involved, climatic conditions, and factors such as weed and insect problems, it is critical that appropriate tillage methods or systems be used to meet the required 30% residue cover. A 30% residue cover generally results in a 50% reduction in soil erosion (McCarthy et al. 1993; Hofman 1997), but the actual amount required to attain such reduction varies depending on the soil type, slope length and steepness, soil drainage, weather conditions, and presence of other conservation practices such as contour tillage and crop rotation (Hofman 1997; Jasa, nd). A 30% residue crop is also a requirement for compliance with federal farm bills (Myers, nd). Other terms for mulch tillage are mulch farming, trash farming, stubble-mulch tillage (SMT), and plowless farming (SSSA 2001).

Early emphasis in the United States for tillage to achieve soil water conservation was to deeply loosen the soil by plowing (Unger et al. 2010). Such practice was largely a carryover that early settlers had used in their home country, mainly Europe, and it virtually eliminated all surface residues. Elimination of surface residues unfortunately resulted in soils being highly susceptible to erosion, both by wind and water. It also resulted in surface sealing during rainstorms, which required additional tillage to loosen the surface crust to again achieve satisfactory water infiltration.

When the benefits of retaining residues on soils to conserve soil and water were first recognized, few tools or methods were available to produce crops under surface residue conditions. This changed in the 1930s when a farmer in Georgia (United States), J. Mack Gowder, used an implement having a 10-cm wide chisel point to loosen the soil and retain plant residues on the surface. By using that implement, which he called a "bull tongue scooter," he tried to mimic the surface cover conditions observed in a forest on his steeply sloping land. This method of tillage became known as "stubble-mulch farming," with that designation attributed to Dr. H.H. Bennett, the author of *Soil Conservation* published in 1939 (Barnett 1987).

Stubble-mulch farming (or tillage) quickly became a recommended practice to conserve soil when the value of keeping residues on the surface was recognized. The goal was to maintain the soil covered with residues as long as possible to reduce runoff and erosion. According to Barnett (1987), SMT was the forerunner of no-tillage (NT), which is "a procedure whereby a crop is planted directly into the soil with no primary or secondary tillage since harvest of the previous crop; usually a special planter is necessary to prepare a narrow, shallow seedbed immediately surrounding the seed being planted" (SSSA 2001).

SMT was widely promoted to help control erosion by wind in the U.S. Great Plains during the major drought of the 1930s. That drought, along with the clean tillage practices being used for crop production at that time, resulted in severe land devastation and hardships for people living in the region (Figure 15.1). Clean tillage involves plowing and cultivation that incorporates all plant residues and prevents growth of all vegetation (e.g., weeds) during the growing season, except for the crop being grown (SSSA 2001). The primary goal for using SMT at that time was to produce a cloddy soil surface and to retain any plant residues on the surface that may have been available. Other goals for using SMT are to perform the tillage at a shallow depth to control weeds; retain plant residues on the surface to decrease runoff, thereby reducing the potential for erosion by water and providing more time for water infiltration; reduce soil water losses due to evaporation; and improve soil water conservation (Allen and Fenster 1986).

The water conservation benefits of crop residues retained on the soil surface were recognized in the 1930s and early 1940s (Duley and Russel 1939; Borst and Woodburn 1942; Barnett 1987). Since then, extensive research dealing with soil water conservation as affected by SMT and other tillage methods that retain crop residues on the soil surface has been conducted at numerous locations, especially in drier regions. Water conservation research, however, has also been conducted at more humid regions and even under irrigated conditions because the need for soil water conservation is widespread.

The amount of residue produced by crops varies greatly, based on the crops grown and conditions under which they are grown. For example, the amount for winter wheat (*Triticum aestivum* L.) residue under dryland (nonirrigated) conditions ranged from 1.3 to 6.5 Mg/ha in studies in the southern U.S. Great Plains (Unger 1994a, 1996). With irrigation, wheat residue yields averaged 9.9 Mg/ha in a study on southern Great Plains (Unger 1994b). Similar differences in residue production occur also for other crops. Differences among crops, however, vary widely with regard to the amount of surface cover provided by a given weight of residue. For example, surface cover was 100% with 8 Mg/ha of wheat (hollow stem) residues, 90% with that amount of grain sorghum [*Sorghum bicolor* (L.) Moench] (pithy stalk) residues, and 37% with that amount of cotton (*Gossypium hirsutum* L.) (woody stalk) residues (Unger and Parker 1976).

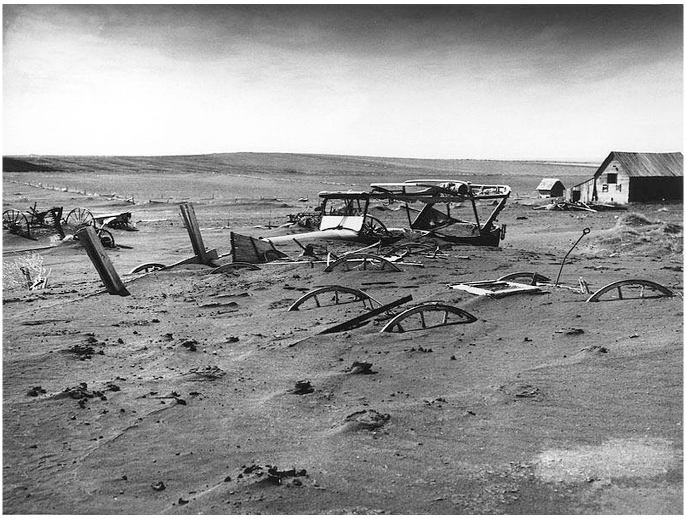

FIGURE 15.1 Devastated land and buried machinery and car in a farmstead in South Dakota during the drought in the 1930s in the U.S. Great Plains. (1936 USDA Photo by Sloan, Image # 00DI0971.)

Because of the large differences in residue production by a given crop or different crops, it is highly important to use an appropriate tillage method for a given crop or cropping condition to maintain adequate surface residues to meet the requirements of mulch tillage. Approximate amounts of crop residues remaining on the soil surface after one pass with different tillage and planting implements are given in Table 15.1. Essentially all residues are retained on the surface when NT is used, which involves only minimal soil disturbance to place the seed in the soil. Under some conditions, in-row subsoiling is used in conjunction with NT, which results in greater soil disturbance, but residue retention would be similar to that shown in Table 15.1 for "machines that fracture soil."

When large amounts of residues are present, one pass with any of the implements mentioned in Table 15.1, except the moldboard or disk plow, may be satisfactory. If additional tillage is required to control weeds or for optimal seed placement, disk implements generally should be avoided. With small residue amounts present, implement selection becomes highly important for retaining adequate residues on the surface. In the case where surface residue amounts are extremely low, all soil disturbances by tillage should be avoided, except as needed to roughen the surface to help control erosion by wind or water. Provided the surface cover requirement is met, all tillage methods mentioned in Table 15.1, except moldboard or disk plowing, qualify as mulch tillage methods. Those methods also meet the surface residue requirement of conservation tillage, which is "operationally, a tillage or tillage and planting combination which leaves a 30% or greater cover of crop residues on the surface" (SSSA 2001). Other terms that denote less soil disturbance and possibly less residue incorporation with soil are minimum tillage and reduced tillage. Minimum tillage is "the minimum

TABLE 15.1
Percentages of Surface Residue Cover Remaining after One Pass with Various Implements

Tillage and Plating Implements	Residue Cover Remaining (%)
Moldboard and disk plows	0–10
Machines that fracture soil (paraplow; ripper, to 30–35 cm depth)	70–90
Chisel Plows	
Straight points	60–80
Twisted points	50–70
Sweeps and field cultivators (including stubble-mulch plows)	60–90
One-way disk	55–80
Tandem or Offset Disk	
25 cm or greater blade spacing	25–50
18–25 cm blade spacing	30–70
Drills and planters	60–95
Natural Weathering	
Overwinter following summer harvest of small grain	70–90
Overwinter following fall harvest of summer crop	80–95

Source: Adapted from Fenster, C.R., Woodruff, N.P., Chepil, W.S., and Siddoway, F.H., *Agron. J.*, 57, 52–55, 1965; Anderson, D.T. In *Conservation Tillage in the Great Plains* (Proc. Workshop, Lincoln, NE, 1968), pp. 83–91. Great Plains Agric. Counc. Publ. 32, 1968; Hill, P.R., Eck, K.J., and Wilcox, J.R., *Agronomy Guide AY-280*, Purdue Univ., West Lafayette, IN, 1994; Bradford, J.M. and Peterson, G.A. In *Handbook of Soil Science*, ed.-in-chief M.E. Sumner, pp. G-247–G-270, CRC Press, Boca Raton, FL, 1999.

use of primary and/or secondary tillage necessary for meeting crop production requirements under the existing soil and climatic conditions, usually resulting in fewer tillage operations than for conventional tillage" (SSSA 2001). Reduced tillage is "a tillage system in which the total number of tillage operations preparatory for seed planting is reduced from that normally used on that particular field or soil" (SSSA 2001). These tillage methods do not require surface residue retention, but may qualify as mulch tillage or conservation tillage if adequate residues are retained on the surface.

NT is essentially the ultimate, that is, the most effective mulch or conservation tillage method, provided residue amounts are sufficient to cover at least 30% of the soil surface. Because primary and secondary tillage operations are avoided, use of NT results in the maximum retention of surface residues and, therefore, is closely related to "conservation agriculture" (CA).

CA "is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment" (FAO 2008). The main objective of CA is economical, ecological, and socially sustainable crop production while achieving soil regeneration or reversing soil degradation. The system requires maintaining a permanent soil cover, minimum soil disturbance, and use of crop rotations.

The main principles of CA are minimum soil disturbance (avoiding tillage operations), maintaining permanent soil surface cover with organic materials, and using rotations involving more than two crops (FAO 2008). At its maximum condition, NT is very similar to CA, but by definition, NT does not meet the requirements for CA. For example, soil loosening with a subsoiler is possible with NT, but such disturbance is not appropriate with CA. Also, a permanent cover of the surface is required for CA, but not for NT. It is recognized, however, that a high level of surface cover by crop residues is essential for NT if soil and water conservation and soil C sequestration are priorities (Unger and Blanco-Canqui 2012). Finally, CA requires use of rotations involving more than two crop species, whereas one crop can be grown continually when using NT. Fortunately, both systems can provide for excellent erosion control and improve water conservation, crop production, and environmental conditions; therefore, either system may have its place in a given locale.

15.3 SOIL CONDITION AND CLIMATE EFFECTS

Agricultural soils vary widely in texture, structure, depth, surface slope, profile characteristics, salinity level, and potential for erosion by water or wind. In addition, agricultural soils occur in regions varying widely with respect to the precipitation level and prevailing temperatures. These conditions strongly influence which type of mulch tillage is best suited for a particular locale and also the potential for conserving (storing) soil water.

Some of the above conditions influence such factors as runoff and soil water-holding capacity, drainage from the profile, and settling. Mulch tillage generally is not appropriate for use on poorly drained soils, especially when large amounts of residues are present. On such soils, water is removed so slowly that the soil remains wet for an extended period and the water table is commonly at or near the surface during a considerable part of the year. Also, surface residue retention by use of mulch tillage may aggravate the poorly drained condition by reducing runoff and retaining water that would to some extent be removed by evaporation. If a properly installed surface or subsurface drainage system is used on these soils to improve productivity, some type of mulch tillage may be appropriate and even water conservation may be of importance at times.

Soil compaction may occur on almost any soil due to farm implement traffic across the surface. Compaction due to farm implement traffic is most likely to occur when soils are wet, which allows soil particles to be more easily rearranged, and when the soil organic matter content is low. A dense, slowly permeable soil layer, termed a plow pan, may develop at the depth of tillage by running the wheels of one side of the tractor in the dead furrow for steering purposes while performing the tillage operation (SSSA 2001). Such plow pan development would occur where moldboard plowing is used. Repeated tillage at the same depth with some implements also results in the formation of plow pans. Hardsetting is a characteristic of the horizons of some soils, usually the cultivated seedbeds that contain unstable aggregates (Greene 2006). Hardsetting results from soil strength development due to matric suction acting within interparticle and interaggregate spaces when the soil is still wet and from temporary cementation of dry soil by poorly ordered silica and aluminosilicates (Bresson and Moran 1995). Soil settling because of heavy rainfall and subsequent soil drying may cause hardsetting of some soils (Karunatilake and van Es 2002). While hardsetting soil horizons tend to be relatively soft while moist, they become unusually hard when dry (Franzmeier et al. 1996).

Compaction, plow pans, and hardsetting of soils may greatly hinder water conservation by reducing water infiltration and, therefore, crop growth and production, unless corrected by use of an appropriate tillage method. For hardsetting soils, NT generally has not been satisfactory (Mead and Chan 1985; Touchton et al. 1989). Generally, favorable crop growth and yields, however, are obtained when such soils are loosened before or at planting with chisel plows or other types of subsoiling implements (Touchton et al. 1989; Abu-Hamdeh 2003; Raper 2006). When adequately loosened, various types of mulch tillage implements, including NT, can be successfully used. Disrupting the dense soil layers also enhances the potential for achieving greater soil water storage.

As previously mentioned, mulch tillage was widely promoted for controlling erosion by wind during the major drought of the 1930s and it has remained an important practice for helping to control erosion by wind. Mulch tillage is also highly effective for controlling erosion by water. For both types of erosion, the level of control achieved increases with increases in the amount of surface cover provided by the residues (Figure 15.2). About 70% cover essentially eliminates erosion by wind and 80% cover essentially eliminates erosion by water. Greatest residue retention is achieved by using implements that cause least disturbance of the surface, namely, soil-fracturing tools, chisels, and sweep implements (Table 15.1). Of course, use of NT generally results in the greatest surface residue retention. Surface residue retention to control erosion is important for conserving the soil resource base and for achieving increased soil water conservation by reducing runoff, improving water infiltration, and reducing wind speeds at the soil surface.

Soil texture strongly influences the amount of water that can be stored in a soil (Figure 15.3) and, to some extent, the rate at which water infiltrates a soil. Sands have the least water-holding capacity, but water infiltration generally is rapid. Water-holding capacity increases with soil clay content and water infiltration is slow on some high-clay-content soils. With a well-developed structure, however, water infiltration may be rapid for soils having high clay content. By contrast, water infiltration usually is low for a soil having a high salt content. Soil texture alone strongly influences a soil's water-holding capacity, but soil texture in combination with soil structure, salt content, and organic matter content has a major impact regarding whether optimum water storage will be achieved for a given

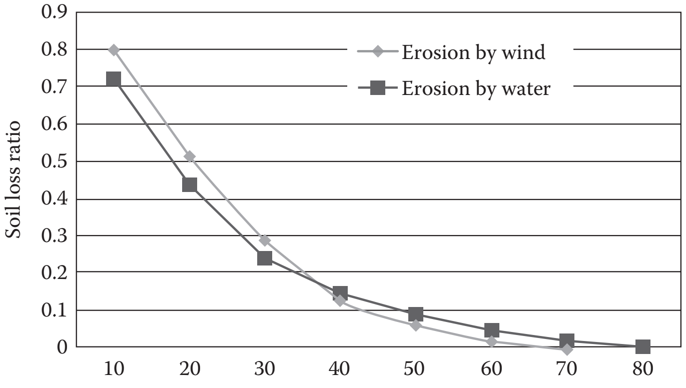

FIGURE 15.2 Relationship between soil loss (movement) ratio (loss with cover divided by loss from bare soil) and percentage of surface covered with residues. (Redrawn from Papendick, R.I., Parr, J.F., and Meyer, R.E., *Adv. Soil Sci.*, 13, 253–272, 1990.)

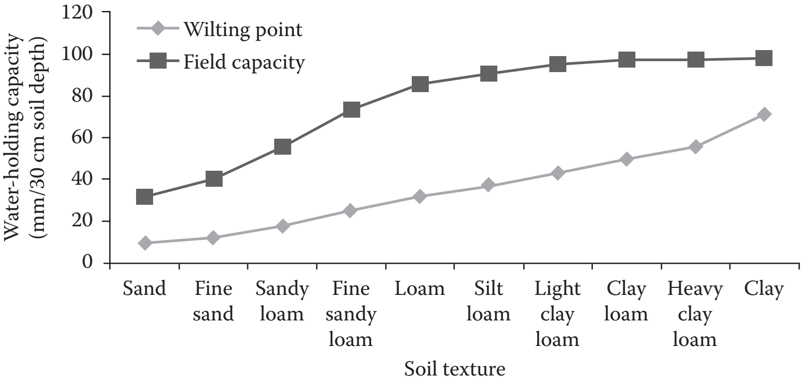

FIGURE 15.3 Typical water-holding characteristics of different-textured soils. The space between field capacity and wilting point values for a given texture represent the amount of water available to plants for that texture. (Redrawn from The Yearbook of Agriculture. In *Water, Yearbook of Agriculture*, ed. A. Stefferud, p. 120, U.S. Dept. of Agric. U.S. Gov. Print. Off., Washington, DC, 1955.)

soil. Regardless of soil structure development, mulch tillage with adequate residue retention can improve the potential for achieving optimum water storage on almost any soil. Use of a cover crop that provides a mulch may alleviate potential salt problems, thereby improving soil water conditions and enhancing crop yields (Mascagni et al. 2002).

15.4 INFILTRATION

The infiltration process represents the critical first step governing conservation of precipitation or irrigation as soil water because it is through infiltration that water enters the soil. Infiltration of water is driven as a result of the soil hydraulic gradient as limited by the conductive properties of both the soil surface and profile. The infiltration process itself is generally independent of climate, but can reflect consequences of cropping systems that incorporate production and management of mulches. Mulches from either crop or synthetic sources directly affect the infiltration process during irrigation or rainfall by intercepting water drop impact that often forms a thin flow-limiting soil surface layer known as a structural seal or crust.

Structural soil seals or crusts form as impacting drops of rain or irrigation water fracture aggregates and detach soil particles that, together with colloids, subsequently, are carried into and through the bulk soil matrix. These soil particles and aggregates transported by the infiltrating water precipitate and occlude the near-surface conducting pores of the bulk soil, thereby resulting in a “washed-in layer” (McIntyre 1958). Gradually, infiltration is reduced enough to cause surface ponding that further accelerates aggregate disruption through slaking (Moore 1981) and dispersion, depending on the electrolytes in the soil or water (Agassi et al. 1981). Fine soil material is deposited at the soil surface to form a thin “skin” layer (~0.1 mm) over any remaining conducting pores, which completes soil crust formation.

The conductive properties of a developing crust have been related, as a first approximation, to the cumulative rainstorm impact energy calculated as the product of rain intensity and the drop size–dependent kinetic energy rate or density (Baumhardt et al. 1990). In that paper, the cumulative rainstorm kinetic energy was linked to the physical changes in the surface soil matrix during crust formation that decreased hydraulic conductance through the crust, K_{cs}/L_c (i.e., crust hydraulic conductivity divided by crust thickness) (Figure 15.4). Crust formation was delayed during initial wetting of the surface aggregates, which absorbed drop impact with no corresponding change in the soil conductance from that of the bulk soil. Continued drop impact on the wetted surface soil fractured aggregates and released primary particles into the infiltrating water to form the crust and cause

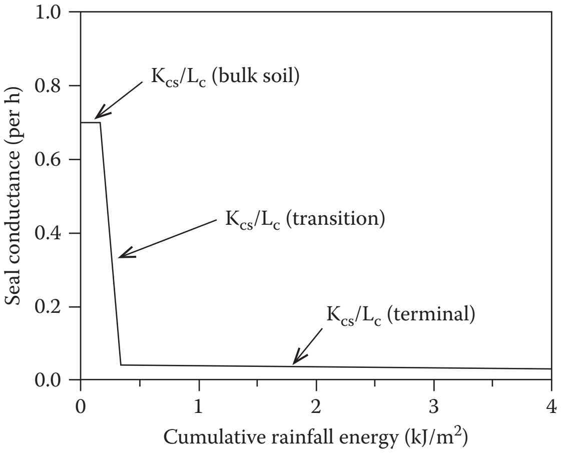

FIGURE 15.4 Example seal or crust conductance, calculated as the ratio of the crust saturated hydraulic conductivity, K_{cs}, divided by crust thickness, L_c, and plotted as a function of cumulative rainfall energy. Initially, crust conductance equals the bulk soil; however, surface wetting and the raindrop impact cause a rapid decrease in crust conductance that transitions to a terminal value. (From Baumhardt, R.L. and Schwartz, R.C. In *Encyclopedia of Soils in the Environment*, ed. D. Hillel, Vol. 1, pp. 347–356, Elsevier, Oxford, UK, 2004.)

a rapid decrease in the transitioning crust conductance to a final or terminal conductance value. Another implication is that in the absence of aggregate slaking or dispersion, an energy-absorbing barrier such as a synthetic material or crop residue mulch will prevent or delay crust formation and the surface soil conductive properties will remain unchanged from those of the underlying bulk soil.

Infiltration is limited to the rainfall intensity or irrigation application rate until the combined effect of the soil hydraulic gradient and conductive properties act to limit the water entry capacity, resulting in runoff and potential for soil erosion. Where soil surface conductive properties are depressed by water drop impact, increasing storm energy due to increased drop size or partial drop interception will govern the rate of crust formation. That is, increasing drop impact accelerates crust formation and, consequently, depresses the infiltration rate at corresponding times during the rainstorm (Figure 15.5). In this example, the transition from infiltration limited to the rainstorm intensity decreased from >40 min with no drop impact to 15 or 20 min for normal 0.0275 or partial 0.0114 kJ/m^2/mm storm energies, respectively. Likewise, the final infiltration rate at 120 min decreased from 17 mm/h to <10 mm/h and resulted in cumulative infiltration of 65 mm with no drop impact compared with 30–35 mm for the normal and partial storm energies, respectively.

15.4.1 SURFACE PROTECTION BY RESIDUES

Except for obstruction of small surface microrelief channels or furrows that retard surface drainage and result in potentially greater opportunity time for infiltration (Musick et al. 1977), the principal benefit of a residue mulch for increasing infiltration is attributed to interception of irrigation or raindrops that delays or reduces soil crust formation. Using an overhead sprinkling device to apply water to nine soils with textures that varied from clay loam to sandy loam, Duley (1939) reported "no striking variability" for either total intake or the intake rate among soils in one of the earliest studies on this topic. Duley also observed that drop interception with straw mulch was almost as effective as a burlap energy barrier to prevent sealing and maintain infiltration rate compared with the corresponding bare soil. Like Duley (1939), others including McIntyre (1958), Morin and Benyamini (1977), and Baumhardt and Lascano (1996) observed that intercepting drop impact with an energy-absorbing barrier, like crop residue, reduces the formation of a crust.

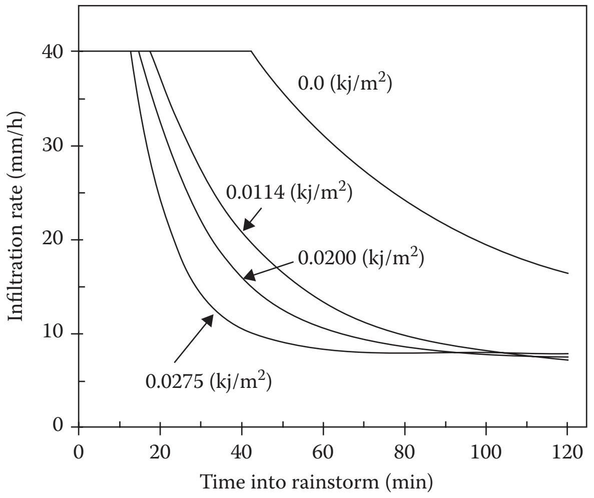

FIGURE 15.5 Infiltration rate (mm/h) is plotted with time during rainstorm for intercepted raindrop impact (0.0 kJ/m^2/mm) compared with storms having progressively higher kinetic energy densities (0.0114–0.0275/m^2/mm) (larger drop sizes). As rainstorm energy increased, crust formation accelerated and decreased infiltration more rapidly. Intercepting drop impact delayed any reduction in infiltration rate. (From Baumhardt, R.L. and Schwartz, R.C. In *Encyclopedia of Soils in the Environment*, ed. D. Hillel, Vol. 1, pp. 347–356, Elsevier, Oxford, UK, 2004.)

The efficacy of mulch tillage to control crust formation and determine infiltration under field conditions and, consequently, storm water runoff and erosion processes, will vary spatially depending on the soil properties and with the degree of residue cover. In a review article, Baumhardt and Schwartz (2004) indicated that tillage practices retaining sufficient residue to intercept drop impact on 40%–60% of the soil surface would be necessary to maintain high infiltration rates. Ruan et al. (2001) evaluated the effects of percent residue cover and geometry on infiltration of water from rainstorms varying in intensity from 25 to 250 mm/h into clay loams and loamy sands using a numerical model. While the cover required to maintain higher infiltration varied with both rainstorm intensity and soil properties, they observed that 40%–80% cover is needed to maintain infiltration. Mulch tillage is often managed to retain residue cover at this level; however, residue production by crops in semiarid regions often is limited. Furthermore, residue from a crop such as cotton often provides insufficient cover to protect the soil and reduce crust/seal formation (Baumhardt et al. 1993). As a result, crust formation progresses rapidly and infiltration of subsequent storms may be depressed by NT compared with SMT (Jones et al. 1994; Baumhardt and Jones 2002).

15.4.2 IMPROVED SOIL CONDITIONS

Residue-conserving mulch tillage typically increases the near-surface soil organic carbon (SOC) compared with conventional tillage. This is because conventional tillage incorporates residue and soil microorganisms rapidly convert residue C into CO_2 (Lal et al. 2004), which is lost to the atmosphere. Conventional tillage and residue removal can accelerate soil erosion through earlier runoff initiation and greater sediment entrainment, which often results in nutrient and collateral SOC losses (Blanco-Canqui et al. 2009). A related benefit of using mulch tillage or a more intensive cropping system that increases SOC is the greater degree of water stable aggregation of surface soil (Liebig et al. 2006) and an increased mean weight diameter of dry aggregates (Pikul et al. 2006), both of which indicate reduced susceptibility to soil erosion.

Increased SOC that improves aggregate stability can support greater infiltration by delaying crust formation and by improving subsurface soil hydraulic properties. For example, the surface saturated hydraulic conductivity (K_s) of a silt loam in Ohio increased with NT that had mulches of 8 or 16 Mg/ha; however, this increased K_s and related infiltration were attributed to earthworm activity (Blanco-Canqui and Lal 2007a). By contrast, infiltration into semiarid Great Plains soils increased immediately following tillage and subsequently declined over time (Pikul et al. 2006), which was consistent with observations by Jones et al. (1994) and Baumhardt and Jones (2002). The related soil K_s was less for mulch tillage (NT) than for conventional tillage, in part, because of greater soil density, or reduced porosity, with NT (Evett et al. 1999).

Where residue production is sufficient to cover at least 30% of the soil surface, a conservation tillage system such as NT or mulch tillage typically benefited overall soil tilth by increasing SOC, which, in turn, improved soil aggregation. Related hydraulic factors such as K_s at the soil surface and with depth may likewise be improved with mulch tillage. Where residue production may not be sufficient to qualify as a mulch tillage system, the soil physical properties such as hydraulic conductivity and bulk density tended to favor conventionally tilled soil.

15.5 EVAPORATION

Controlling the evaporation process may represent the greatest challenge to soil water conservation for agricultural production systems in arid and semiarid regions. Evaporation is often partitioned into the loss of water from the soil and from crop (transpiration). Under fixed drying conditions, evaporation from bare soil has been represented as a three-stage process (Lemon 1956) that is initially limited by the amount of energy delivered to a wet surface (Figure 15.6). With continued drying, water flow to the surface is limited by the soil hydraulic properties and evaporation decreases as a function of the square root of time (Gardner 1959) or as “falling rate” Stage 2 evaporation (Ritchie 1972). The rate of evaporation during Stage 3 is nearly constant and very low because the soil has dried. Residue management efforts have been generally directed toward modifying Stage 1 and Stage 2 evaporation that maintained a progressive reduction in evaporation as residue cover increased, but not during Stage 3 evaporation (Bond and Willis 1969).

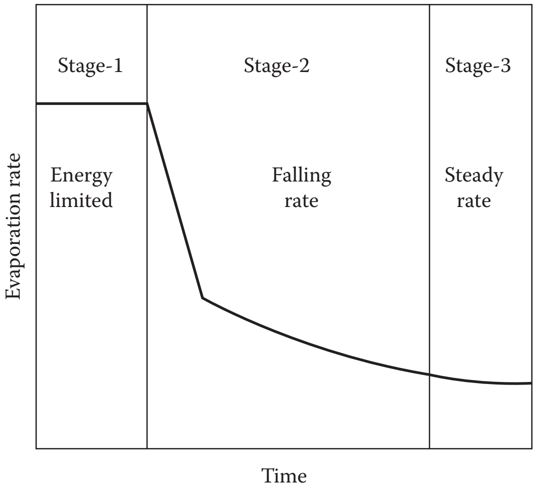

FIGURE 15.6 Conceptualized water evaporation rate plotted with time to illustrate a three-stage process for bare soil. Stage 1 evaporation is limited by energy delivered at the soil surface, while a “falling rate” of evaporation occurs during Stage 2, and evaporation ends with a low nearly steady rate during Stage 3.

Mulch tillage utilizes residue-retaining management practices to decrease evaporation and, consequently, increase storage of precipitation as soil water for subsequent crop use. Early experiments often led to the conclusion that reduced crusting, which resulted in increased infiltration, was a primary benefit of mulch tillage (Duley 1939). Further investigation during a 4-month period by Duley and Russel (1939) identified 54% rainfall conservation in straw-covered plots compared with 20% for bare plowed or disk-tilled soil and 28% for basin tillage that prevented any runoff. In that study, they concluded that evaporative water loss from bare soil was almost equivalent to the water conserved by preventing runoff using basin tillage.

In an effort to characterize crop residue effects on soil water conservation, Russel (1939) compared evaporation from soil cylinders under natural conditions that were shaded, shaded and wind-sheltered, or straw-mulched with evaporation from the cylinders exposed to normal wind and sun. Evaporation from the "densely shaded" soil decreased 36% because of reduced net radiation at the soil surface (R_{NS}). Sheltering the soil from wind further reduced evaporation by 17% as a result of greater aerodynamic boundary layer resistance. By contrast, straw mulching decreased evaporation by 73% from that of soil exposed to normal wind and sun because mulches reflect and intercept radiation, shelter against wind, and modify the vapor diffusivity at the soil surface. Surface energy balance factors governing evaporation that were indirectly compared experimentally by Russel (1939) have since been further investigated and described in a more recent review article by Horton et al. (1994). The surface energy balance can be revealing in quantifying crop residue effects on evaporation from soil and crops.

15.5.1 ENERGY AT THE SURFACE (SOLAR)

The soil surface energy balance equates the R_{NS} to various heat flux components including the soil heat flux (G) as described by Fourier's law of heat conduction, sensible heat flux into the air (H_{SOIL}), and latent heat flux (LE_{SOIL}) or evaporation according to Equation 15.1:

$$R_{NS} = G + H_{SOIL} + LE_{SOIL}, \tag{15.1}$$

assuming that energy flux into heat storage is negligible (Horton et al. 1994). For a bare soil system, the R_{NS} is the sum of incoming irradiance, both longwave (L_i) and global shortwave (S_g) adjusted for the albedo (α) reflectance correction, minus the reflected longwave radiation (L_o) according to Equation 15.2:

$$R_{NS} = (1 - \alpha)S_g + L_i - L_o \tag{15.2}$$

The H_{SOIL} is a function of the volumetric heat capacity of air, the difference in soil surface and air temperatures, and the resistance to heat flux. Similarly, LE_{SOIL} is a function of the latent heat of vaporization of water, the difference in absolute humidity between the soil and air, and the resistance to LE_{SOIL}.

In mulch tillage systems, the residue cover acts directly at the soil surface to modify albedo, temperature, absolute humidity, and the resistance to sensible heat flux as well as LE_{SOIL} (Lascano and Baumhardt 1996). By increasing the reflection of incoming global irradiance and decreasing the surface emissivity, surface residues essentially displace radiation absorption upward from the soil surface. Residues are also less conductive to absorbed energy than mineral soils and resist surface heat exchange. Crop residue also affects both latent and sensible heat fluxes by increasing aerodynamic roughness, thus expanding the aerodynamic boundary layer, and by modifying soil surface temperature, water content, and related gradients. For example, total aerodynamic resistance increased by 15% after increasing the wheat residue height from 0.4 to 0.6 m, which also intercepted approximately 12% more global irradiance (Baumhardt et al. 2002).

Partitioning evapotranspiration into evaporation from the soil and transpiration from the crop canopy establishes the interacting effects of mulch tillage residues and a growing crop on water use and yield. Lascano and Baumhardt (1996) conducted one of the earliest efforts to calculate evapotranspiration from a crop grown on a residue-covered soil by using an energy balance procedure that estimated net irradiance, sensible heat exchange, and evaporation from the soil and canopy surfaces. The key feature of their approach was radiative energy transfer for distributing incoming irradiance to the cotton crop canopy, wheat residues at the soil surface, and any bare soil. During the early part of the cotton-growing season, wheat residues intercepted and reduced the net irradiance at the soil surface compared with the much higher net irradiance for conventional bare soil, which resulted in greater soil water evaporation. Because of a fuller canopy and high leaf area index during the later part of the growing season, the canopy net radiation was greater, which diminished the differences in evaporation or sensible heat flux at the soil surface, regardless of residue cover. Nevertheless, the combined seasonal soil and cotton canopy evaporation was approximately 330 mm over a 100-day period for both bare and residue-covered soils as a result of the common global irradiance. Estimated crop evaporation (transpiration) increased from 164 mm for bare soil to 223 mm for residue-covered soil. The increased crop transpiration resulted in a net cotton yield increase from 613 kg/ha for bare soil to 830 kg/ha with residue that when divided by the corresponding transpiration amount averaged a constant conversion of 0.38 Mg lint/m^3 water. The corresponding water-use efficiency values for the combined 330 mm of soil and crop evapotranspiration were approximately 0.19 and 0.26 Mg/m^3 for the bare and residue-covered soils, respectively (Lascano et al. 1994).

15.5.2 TEMPERATURE EFFECTS

Mulch tillage effects on soil temperature are a result of the complex balance between the net irradiance that decreases with the greater albedo for soil that is untilled (Schwartz et al. 2010) or residue covered (Lascano and Baumhardt 1996) and the energy losses due to sensible and LE_{SOIL} at the soil surface. That is, residue reduces net radiation, resulting in cooler soil temperatures, and mulch tillage residue tended to dampen diurnal soil temperature fluctuation compared with bare soil possibly due to greater heat capacity of increased soil water. Unger (1978) reported progressively cooler soil temperature as straw mulches increased from 0 to 12 Mg/ha during sorghum-growing season. He also noted a reversal in soil temperatures resulting in warmer mulch-covered soil when bare soil temperature decreased below 0°C. This was similar to later observations during wheat growth on the North China Plain by Chen et al. (2007).

15.6 COVER CROPS

Cover crops are used to increase the amount of crop residue left on the soil surface. Typically, cover crops are planted in the autumn, after harvest of the cash crop, and grown until a few weeks before planting a crop the following spring. This practice helps reduce erosion by water and wind during the winter months, particularly with crops such as cotton and potatoes (*Solanum tuberosum*) that leave little residue on the field. Cover crops have also been used as green or living mulches to provide nitrogen to the cash crop (Pedersen et al. 2009; Ochsner et al. 2010). In this case, a legume is planted and grown until bloom to maximize the amount of nitrogen available to the following crop. At that time, the legume cover crop is terminated chemically or mechanically with the following crop planted very shortly afterward to optimize nitrogen use. An alternative is to plant the cash crop into the living legume cover (i.e., living mulch) and either terminate the cover crop in the entire field or just a strip over the cash crop row. Living mulches present some challenges because cover crops compete for resources, mainly water, with the cash crop.

Grass species such as oats (*Avena sativa*), rye (*Secale cereale*), ryegrass (*Lolium* genus), and wheat also are popular choices as cover crops. These can be planted with a drill or broadcast over the soil surface, but the seeding rate should be increased when broadcasting to obtain a good stand.

When managed properly, grass cover crops can produce a significant amount of biomass, with production of 4 Mg/ha or more dry matter having been reported for different cover species (Daniel et al. 1999; Bowen et al. 2000; Locke et al. 2005; Sainju et al. 2005). Management of such biomass can be challenging and some modifications to planting and tillage equipment might be needed. A NT planter equipped with row cleaners is usually required when planting into cover crop residue, either under NT or strip-till conditions. Planting of the cash crop can be done with the cover crop residue left standing or after it is flattened with a roller to form a dense mat of mulch over the soil surface (Kornecki et al. 2009). Either way, it is recommended to terminate the cover crop 2–3 weeks before planting the cash crop to allow the soil profile to be recharged with water and avoid competition (Reeves 1994).

Benefits of a high residue cover crop are many, including weed suppression, increased water availability, reduced erosion, nutrient recycling, and eventual improvement of soil quality from the addition of organic matter. Water availability is of special interest to this discussion, so we will discuss it in some detail. Gains in plant available water due to the use of cover crops is commonly attributed to increases in soil organic matter, which in turn improves soil aggregation, water infiltration, and soil water retention. Increasing organic matter content in the soil can take a considerable amount of time and varies with soil type and climate. However, some gains in water availability from cover crop use can be attributed to the mulch effect of the cover biomass, which reduces soil water evaporation and enhances infiltration by a reduction in soil surface crusting and by increased water flow into root channels. In central Alabama, an increase in soil water content was observed in the first year with the use of rye or wheat as a cover crop when compared with a no-cover control (Figure 15.7). This difference in soil water content was equivalent to approximately 25 mm of additional water in the top 50 cm of the soil profile. Although these cover crops produced a large amount of biomass (~4 Mg/ha), this increase in soil water content might not be typical and can be affected by other factors such as soil type, cash crop, cover crop management, and weather conditions.

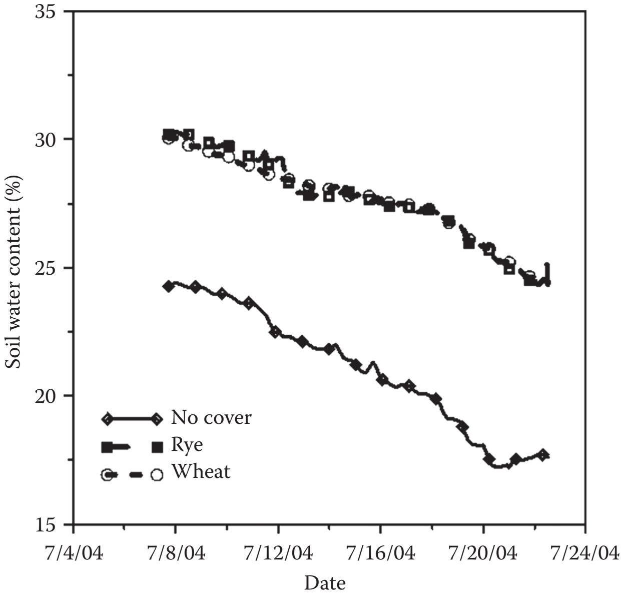

FIGURE 15.7 Volumetric soil water content during the first year of a study comparing rye and wheat as cover crops to a no-cover control on cotton near Prattville, in central Alabama. (Unpublished data of Arriaga, F.J. and Balkcom, K.S., USDA-Agricultural Research Service, National Soil Dynamics Laboratory, Auburn, AL.)

The amount of biomass produced is important because it affects the magnitude of the impacts the cover crop will have on the following crop. As the amount of biomass produced by the cover crop increases, benefits associated with the use of a cover crop seem to also increase. A cone penetrometer is a device consisting of a metal rod with a cone-shaped tip that is pushed into the ground to determine the relative compaction level of soil layers, known as penetration resistance or cone index. Cone index data collected from a study conducted on a loamy sand showed a decrease in cone index values in the soil profile as biomass levels increased (Figure 15.8). Penetration resistance decreased with increasing cover crop biomass amounts, which was probably caused by increased cover crop root growth and activity. In this case, differences in soil water were minimal because the penetrometer readings were collected when the soil water contents

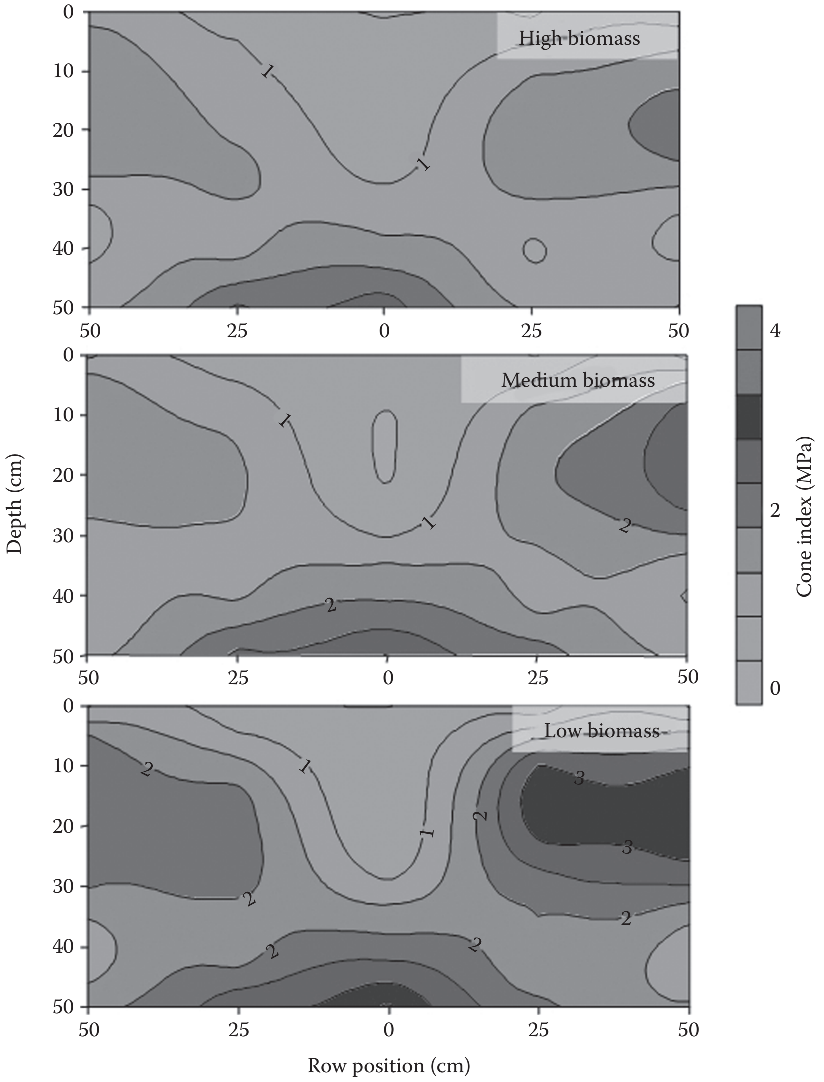

FIGURE 15.8 Penetration resistance for a coastal plain soil with three levels of rye biomass (high = 5.3 Mg/ha; medium = 2.6 Mg/ha; low = 0.2 Mg/ha) during the 2005 spring season before cash crop planting. Note that the areas with low cone index values in the center of the contour plots are associated with an in-row tillage operation and the higher values on the right with the trafficked row. (Unpublished data of Arriaga, F.J. and Price, A.J., USDA-Agricultural Research Service, National Soil Dynamics Laboratory, Auburn, AL.)

were at or near field capacity. Other researchers have concluded that a well-established and managed cover crop producing a large amount of biomass can be as effective as a strip-till operation (Raper et al. 2000, 2005). Cotton yield under NT conditions with rye as a cover crop was statistically similar to those of strip-till operations with a cover crop (i.e., there was no benefit from the tillage operation).

Recent interest on bioenergy production from cellulosic materials has created concerns over the long-term sustainability of agricultural production systems and environmental impacts. Cover crops can potentially be used to offset soil carbon imbalances that can be caused by the harvest of plant residues for bioenergy purposes. Harvest of plant residues would typically take place, for example, after corn (*Zea mays* L.) grain harvest. A winter cover crop could be planted after stover harvest. This cover crop would protect the soil from erosion due to snowmelt or rainfall during winter and early spring. Organic matter in the soil would be improved during the decomposition of the cover crop residue. Adding a cover crop to a crop management system essentially integrates a crop rotation within the same year, which is similar to the use of cover crops after cash crops such as potatoes and peanuts (*Arachis hypogaea*) that leave little residue after harvest.

Integrating cover crops into crop management rotations needs to be done carefully considering other factors such as precipitation amount and reliability in the region involved. Including cover crops in a cropping system can improve water conservation when mulch tillage is used to retain most of the residues on the soil surface, thereby improving water infiltration and reducing soil water evaporation. Use of cover crops is well adapted to humid regions where precipitation generally is adequate so that competition for soil water with crop plants is minimized. By contrast, in regions where precipitation is less abundant and reliable, competition for water generally increases water stress in crop plants when cover crops are involved, which results in lower yields. Although some favorable results with cover crops have been obtained in less humid regions (Folorunso et al. 1992; Reinbott et al. 2004), the use of cover crops generally is not advisable under dryland (nonirrigated) conditions in semiarid and arid regions where precipitation usually is limited and often highly erratic (Unger and Vigil 1998; Baumhardt and Lascano 1999).

15.7 CROP ROTATION IMPACTS

Use of crop rotations has long been an important management practice. A crop rotation is a planned sequence of crops grown in succession on the same field, as contrasted to growing one crop continually or several crops in a variable sequence (SSSA 2001). With respect to mulch tillage, use of crop rotations is especially important when the crops being grown differ widely in the amount of residues they produce. Under such conditions through careful management, residues from a crop that produces a large amount or provides for a high degree of surface cover may provide adequate surface cover throughout the growth period and even during the fallow period after harvest of the succeeding crop. This is illustrated in Figure 15.9 for a winter wheat–fallow–grain sorghum–fallow (WSF) rotation that results in two crops in 3 years. In the upper photo, some wheat residues remained on the surface after harvest of grain sorghum that was planted about 11 months after the wheat was harvested. In the lower photo, some sorghum residues remained after harvest of wheat that was planted about 11 months after the sorghum was harvested. In both cases, the combined surface residues provided adequate surface cover to meet the 30% residue cover requirement of mulch tillage. These results were for a dryland (nonirrigated) study in the U.S. southern Great Plains (Unger 1994a). In Australia, Freebairn et al. (2006) reported that carryover residues from a previous cereal crop can provide soil protection throughout the fallow period and crop phase for subsequent low residue producing crops such as sunflower (*Helianthus annuus* L.), canola (*Brassica* spp.), chickpea (*Cicer arietinum*), and cotton. Through use of an appropriate mulch tillage method, high amounts of residues from a crop such as corn can be managed to provide benefits for a low-residue-producing crop such as soybean (*Glycine max* L.) (USDA-SCS 1999) when such crops are grown in a rotation.

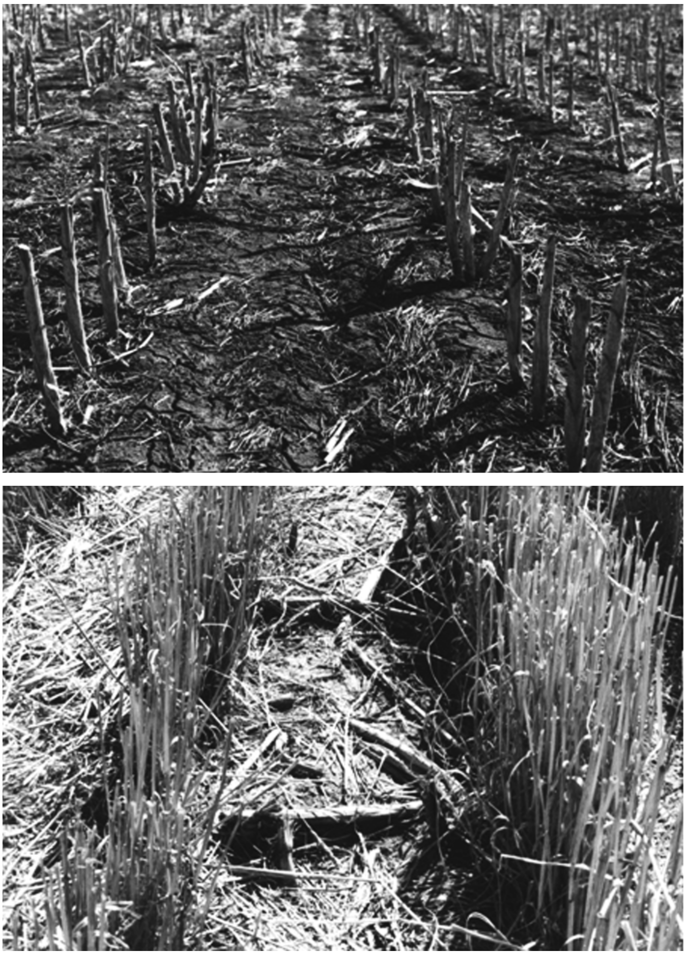

FIGURE 15.9 Residues of wheat and sorghum on the surface in a winter wheat–grain sorghum–fallow cropping system under dryland (nonirrigated) no-tillage conditions. Upper photo: standing sorghum (most recent crop) stalks with stubble of the previous wheat crop lying on the surface. Lower photo: standing wheat (most recent crop) stubble with stalks of the previous sorghum crop lying on the surface.

In addition to providing adequate residues to meet the surface cover requirements of mulch tillage, use of crop rotations also provides for insect, plant disease, and weed control (Peel 1998; Skillman 2001; Carr 2006; Freebairn et al. 2006; Rehman 2007). Crop rotations provide insect control because some insects feed only on specific plant species. By including totally different plant species in the rotation, the preferred species is no longer available, thus causing the particular insect to either leave or die (Poole, nd). Likewise, plant disease control is achieved because a given disease usually is prevalent only on a specific plant type. By limiting or controlling insect and disease problems, adequate plant growth is possible, thereby potentially providing adequate residues to be managed by mulch tillage to achieve water conservation. (Impacts of mulch tillage on weeds are discussed later.)

In addition to providing insect, disease, and weed control benefits, other benefits from using crop rotations include improved soil fertility, tilth, and aggregate stability; reduced soil erosion; improved soil water conditions; reduced allelopathic and phytotoxic effects; and possibly greater economic returns (Peel 1998; Carr 2006). These benefits generally are enhanced by using mulch tillage, thereby leading to potentially improved crop growth and production, which in turn can lead to improved conditions for the next crop in the rotation.

15.8 WEED CONTROL WHEN USING MULCH TILLAGE

Weeds have long been an important agricultural problem. Weeds compete with crop plants for nutrients, water, light, and space, and, if not effectively controlled, may greatly diminish crop yields. In extreme cases, crops may not produce a harvestable yield when weeds are not controlled. Effective weed control, therefore, is highly important for achieving satisfactory crop production and such control is possible through the use of tillage and herbicides. Modern cropping systems use cultivars that have been modified through genetic engineering to allow for over-the-top application of some herbicides. Each of these methods has a place where mulch tillage is used.

15.8.1 TILLAGE

Some type of tillage has been considered essential through the years to control weeds (Triplett and Dick 2008), with clean tillage being the prime method until mulch tillage was introduced in the 1930s and 1940s. Unfortunately, clean tillage had to be repeated whenever weed control again became necessary. Also, by incorporating all residues, surface soil crusting, high potential for erosion, and limited potential for conserving water were common where clean tillage was used.

While clean tillage, by definition, involves incorporating all surface residues, some retention of surface residues is implied by the term "conventional tillage." Conventional tillage involves the primary and secondary tillage operations normally used to prepare a seedbed and to cultivate a crop in a given geographical area. It usually results in <30% of the surface covered by residues after completing the tillage operations (SSSA 2001). All residues may be incorporated by using conventional tillage when, for example, moldboard plowing is used, and, therefore, it would be equivalent to clean tillage. By contrast, conventional tillage could also be similar to mulch tillage if the operations being used result in >30% surface cover by residues.

Mulch (conservation) tillage was used on 37% of the cropland in the United States in 1998, with a continuing upward trend indicated. Although use of mulch tillage is increasing with about 23% of the total cropland in the United States being planted under NT conditions in 2004 (Triplett and Dick 2008), conventional tillage continues to be widely used in the United States (Walters and Jasa, nd). By contrast, greater percentage adoption of mulch tillage than in the United States has occurred in some South American countries (Argentina, Bolivia, Brazil, Paraguay, and Uruguay) where NT is used on 69% or more of the cropland. High percentages of NT adoption have also occurred in some regions in Canada and Australia, with substantial adoption also occurring in some other countries (Derpsch and Friedrich 2009).

Clean or conventional tillage methods generally control annual and biennial weeds effectively because the entire plant is destroyed. Clean tillage, however, only suppresses perennial weeds that may grow back from vegetative parts. Some winter annual weeds are difficult to control with clean tillage because they become established along with the winter crop (e.g., winter wheat) (Kettler et al. 2000). Some summer weeds also are difficult to control with clean tillage (Wortman and Jasa 2009). Effective weed control can be achieved by using an appropriate mulch tillage method in many cases, but control also is difficult with mulch tillage for problem weeds as noted earlier for clean tillage. While the primary goal is to control the weeds, the long-term goal should be retaining adequate residues on the soil surface to achieve the benefits of using mulch tillage. Because all methods incorporate some residues (Table 15.1), tillage method selection is highly important, especially if additional tillage may be needed for further weed control. The method selected will be influenced by weed type and growth stage, surface residue level, soil conditions, and climatic region, among other factors.

For effective control, the tillage method should result in optimum separation of the weed roots from the soil or complete destruction of the weed. Soil fracturing and chisel implements (Table 15.1) are not satisfactory for controlling weeds. Generally, good control can be achieved with sweep-type implements (field cultivators and stubble-mulch plows), one-way disks, and disk harrows. If the

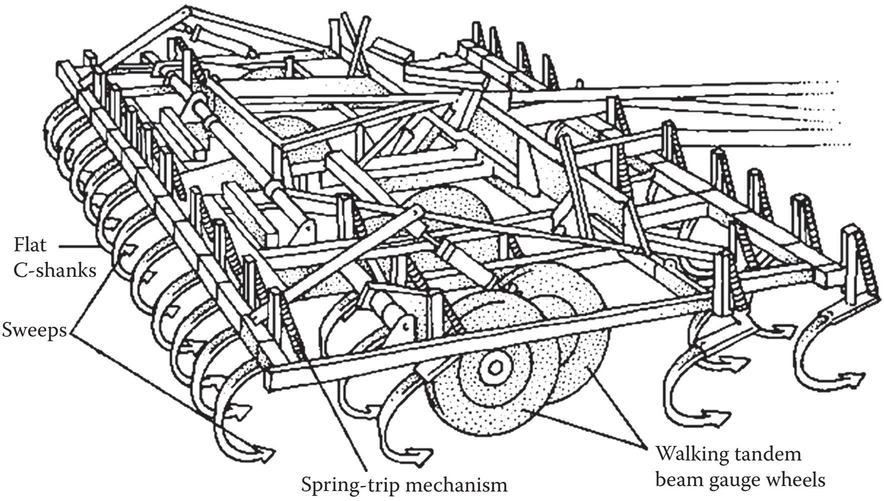

FIGURE 15.10 Schematic view of a field cultivator. (From SARE [Sustainable Agriculture Research and Education]. nd,a. Steel in the field: A farmer's guide to weed management tools [Dryland crops field cultivator (with sweeps)]. http://www.sare.org/publications/steel/pg88.htm [accessed June 10, 2010].)

goal of tillage in addition to controlling the weeds is to retain adequate surface residues, the residue amount present will strongly influence whether it is appropriate to use sweep-type implements or whether some type of disk implement can be used. Disk implements generally are highly effective for controlling weeds, but also incorporate a relatively high percentage of residues each time they are used (Table 15.1). With high amounts of residues initially present, one or possibly two operations with a disk implement may be satisfactory for controlling weeds and still retain adequate residues on the surface.

Field cultivators (Figure 15.10) and stubble-mulch plows (Figure 15.11) are mulch tillage implements used to till or prepare a soil in such a way that plant residues and other materials remain on the soil surface. These implements have V-shaped sweeps or straight blades that undercut the soil surface at a depth ranging from about 5 to 15 cm (Duley and Mathews 1947). Sweep widths vary widely among different plows, depending on the manufacturer or particular model of a plow. Likewise, widths of sweeps or blades on stubble-mulch plows also vary widely. Some stubble-mulch plows have blades that are 2 m or more wide. By undercutting the soil surface, these implements loosen and break up the soil if it has the proper water content. Such tillage is highly effective for controlling weeds, again if the soil water content is proper. Improved weed control is achieved when field cultivators or stubble-mulch plows are equipped with rod weeders (Figure 15.12). Rod weeders have a rotating subsurface rod that pulls and uproots weeds, thereby depositing them on the soil surface for exposure to the elements. Where a heavy infestation of weeds is present, the net effect of rod weeding can be to create mulch comprised of weed residues (SARE, nd,c).

To control weeds, tillage with a field cultivator or stubble-mulch plow generally is most effective where soils are relatively dry as frequently is the case in a region such as the U.S. Great Plains. SMT, however, was also found to be effective in a more humid region (New York) as early as the 1950s (Free 1953).

15.8.2 HERBICIDES

Herbicidal weed control began in the 1800s with copper sulfate being used first in 1821 (Reinhardt and Ganzel 2007) and iron sulfate being used to control broadleaf weeds first in 1896 (Tvedten 2001). The first synthetic organic chemical (2-methyl-4, 6-dinitrophenol) was introduced in 1932

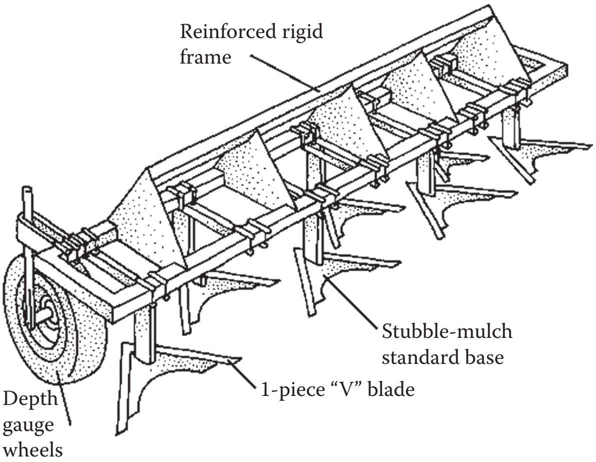
Reinforced rigid frame
Stubble-mulch standard base
1-piece "V" blade
Depth gauge wheels

FIGURE 15.11 Schematic view of a stubble-mulch plow. (From SARE [Sustainable Agriculture Research and Education]. nd,b. Steel in the field: A farmer's guide to weed management tools [Dryland crops stubble mulch blade plow]. http://www.sare.org/publications/steel/pg90.htm [accessed June 10, 2010].)

(Reinhardt and Ganzel 2007). A new era of herbicidal weed control began in 1942 when 2,4-D [(2,4-dichlorophenoxy) acetic acid] was developed. Numerous herbicides now are available with applications possible before planting or after establishing a crop without damage to the crop. A sound understanding is essential regarding which herbicides can be used to avoid damage to the current crop or subsequent crops in a rotation.

Effective weed control during a crop's growing season is essential for reducing or eliminating direct competition between weeds and crops for soil water. Weed control in the interval between crops is also highly important to achieve soil water storage in preparation for the next crop. By using herbicides, less frequent or elimination of tillage, as with NT, is possible. By reducing or eliminating tillage to control weeds, exposure of moist soil to the atmosphere is limited, thereby reducing evaporative soil water losses. Also, more residues are retained on the surface when tillage is reduced or eliminated, thereby increasing the potential for improved soil water conservation as a result of reduced runoff and improved water infiltration.

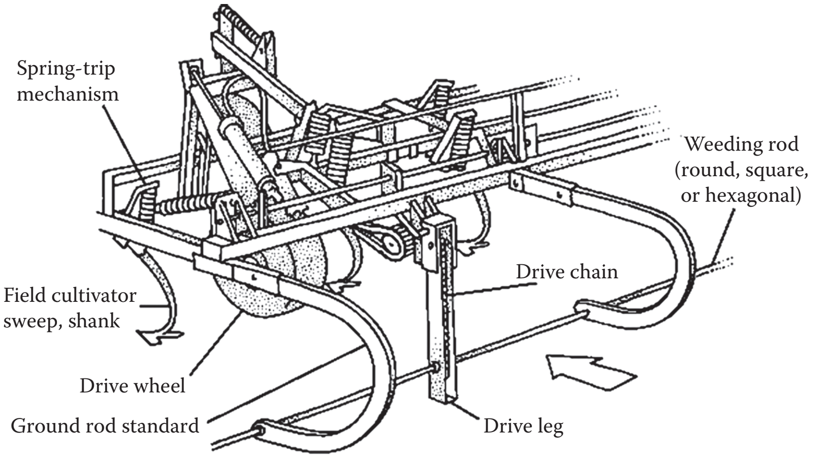
Spring-trip mechanism
Weeding rod (round, square, or hexagonal)
Drive chain
Field cultivator sweep, shank
Drive wheel
Ground rod standard
Drive leg

FIGURE 15.12 Schematic view of a field cultivator with an attached rod weeder. (From SARE [Sustainable Agriculture Research and Education]. nd,c. Steel in the field: A farmer's guide to weed management tools [Dryland crops rod weeder]. http://www.sare.org/publications/images/pg_92.gif [accessed June 9, 2010].)

Effective weed control is essential, especially during the crop's growth period, for successful crop production. With respect to water conservation, weed control in the interval between crops is important also, but where, for example, a dryland crop produces inadequate residues to provide erosion control and/or achieve satisfactory water conservation, allowing weed growth early in the interval between crops may be an option (Bennett 1939; Schillinger and Young 2000). Satisfactory soil water conservation is still possible under such conditions, provided the weeds are terminated in a timely manner and before they produce seed, but still allowing the weed residues to remain on the surface to reduce runoff, improve water infiltration, and reduce evaporation. Use of such practice, termed "delayed SMT," resulted in soil water contents when winter wheat was planted similar to those resulting from repeated use of SMT to control weeds throughout the fallow period (Johnson and Davis 1972).

As with tillage, there may be problems with herbicidal weed control, with undoubtedly the greatest problem being the development of herbicide resistance in some weeds. Herbicide resistance refers to the inherited ability of a weed or crop biotype to survive a herbicide application to which the original population was susceptible (Gunsolus 2008). Resistance of weeds to triazine herbicides was found in 1968 and 120 weed biotypes were resistant to those herbicides by 1991. Resistance to 15 other herbicide families also was found throughout the world by 1991, with additional cases of resistance found since that time (Gunsolus 2008). Where herbicide-resistant weeds are a problem, NT will not be appropriate because it is based on the use of herbicides for controlling weeds and alternative herbicides are not available for controlling the herbicide-resistant weeds. Under such conditions, SMT generally would be more appropriate. In some cases, NT fields are occasionally stubble-mulch plowed, which helps control such problem weeds and increases crop yields as compared with those in undisturbed NT fields (Kettler et al. 2000). Use of crop rotations that expands the diversity of herbicide mode-of-action can be crucial for reducing problems with herbicide-resistant weeds.

15.8.3 Herbicide-Resistant Crop Production Involving Genetic Engineering

With respect to weed control, genetic engineering involves selecting herbicide-tolerant genes that naturally occur in a given crop cultivar or cell culture and incorporating them through traditional breeding processes into crop varieties or hybrids (Penn State 2010). Through genetic engineering, it is now possible to use highly effective, quick-acting herbicides to control weeds in some actively growing crops that are resistant to those herbicides. Development of crops resistant to some herbicides has greatly expanded the opportunity to control problem weeds in some crops. For example, because of genetic engineering, glyphosate [N-(phosphonomethyl) glycine] can be applied to control weeds in glyphosate-resistant cultivars of soybean, corn, and canola (Padgette et al. 1995; Moll 1997; Rasche and Gadsby 1997). Growing of crops altered by genetic engineering is being rapidly adopted by producers in many countries worldwide (Duke 1999; McHughen 2006). Growing herbicide-resistant crops allows producers to more effectively use mulch tillage practices such as NT and reduced tillage (Duke 1999), thereby increasing the opportunity for improving soil water conservation when more residues are retained on the soil surface. When herbicide-resistant crops are grown, volunteer plants of the crop may cause problems because they also would be resistant to the herbicide, thus possibly requiring some tillage to control those plants.

15.9 IMPACT OF RESIDUE REMOVAL FOR BIOFUEL PRODUCTION

Crop residues retained on the soil surface, which are important for conserving soil water, also are highly important for controlling soil erosion by wind and water (Figure 15.2). Maintaining crop residues on the surface by using mulch tillage, therefore, is highly important for maintaining the soil resource base for sustainable crop production and possibly enhanced production for an ever-increasing world population. As discussed in previous sections, water and soil conservation generally increases with increases in residue retention on the surface. Removing residues for biofuel production, at least from some soils, therefore, could negate their beneficial effect on sustaining or improving conditions for sustained or improved crop production.

The use of crop residues as feedstock for cellulosic ethanol production has received much interest in the United States and some other countries, with some commercial plants being built for its production in the United States (USDOE 2007). Corn stover is widely considered the main cellulosic feedstock for biofuel production (Graham et al. 2007), but residues of wheat and sorghum are also feedstock for biofuel production (Sarath et al. 2008). Production of ethanol from renewable sources is important and should be pursued, but the practice of removing crop residues as biofuel feedstock must be carefully examined relative to its impacts on soil conditions, including water conservation, crop production, and environmental quality.

The removal of crop residues for any purpose can negatively and positively impact water and soil conservation, with negative impacts prevailing under long-term conditions (Wilhelm et al. 2007). Indiscriminate residue removal is not advisable in semiarid regions where precipitation is low and variable, thus resulting in low residue production. In more humid regions or with irrigation, it may be possible to remove some residues without adversely affecting soil conditions and water conservation, provided some residues are retained and managed through use of appropriate tillage methods.

The removal of crop residues influences crop production because it often reduces the amount of water available to plants. It may also affect production due to abrupt fluctuations in soil surface temperature and loss of plant nutrients. In Nebraska, complete removal of corn stover from a silty clay loam in a 4-year study involving NT reduced corn grain and biomass yields by about 23% (Wilhelm et al. 1986). The amount of crop residues on the surface may explain 95% of the variability in grain and biomass yields (Wilhelm et al. 1986; Blanco-Canqui and Lal 2007b).

Impacts of residue removal on corn production are site-specific and depend on factors such as soil type, topography, tillage method, climate, and duration of stover management. Crop production can be more adversely affected by residue removal from sloping, erosion-prone, and well-drained soils than from flat and clayey soils (Linden et al. 2000).

In some soils or ecosystems, it may be feasible to remove a portion of the crop residue for biofuel production in the short term without increasing the potential for erosion by water and wind, hindering soil water conservation, or reducing crop yields. Indeed, removing some residues may improve seed germination, facilitate planting, increase N mineralization, and reduce pest infestations. Lower soil temperatures under surface residues often results in slower seed germination, especially in colder regions as, for example, the northern United States and Canada. Corn emergence in Canada was as much as 30% lower in mulched plots than in unmulched plots (Dam et al. 2005). On three soils in Ohio, corn stover removal from long-term NT soils enhanced seed germination. Without stover removal, emergence was delayed by up to 3 days as compared with that on soils where all stover was removed (Blanco-Canqui et al. 2006). In both studies, the delayed emergence did not reduce crop yields. Plants in plots with low residue cover often grow taller during the first few weeks, but the height differences often diminish rapidly with time.

On wet and cold mulched soils, the combination of reduced germination, proliferation of weeds and pests, and nutrient immobilization may lower crop yields. In southwestern Wisconsin, corn yield decreased on two silt loams when stover cover was doubled (Swan et al. 1994). Yields of continual corn decreased during the last 4 years of a 13-year study when 2, 4, 8, or 16 Mg/ha of stover mulch was applied to a silty clay loam in Iowa (Morachan et al. 1972).

The impacts of removing residues on soil water conservation, other soil conditions, and crop production are site-specific and information regarding maximum permissible removal rates is limited. Involved are such factors as tillage methods and cropping systems being used, soil characteristics, and climatic zones. Based on a computer model, mainly for the U.S. Corn Belt region, 20%–50% of the residue produced may be removed without adversely affecting the residues needed to control erosion (Graham et al. 2007). Those estimates, however, did not deal with water conservation, which undoubtedly would require different amounts of surface residues to achieve optimum water conservation.

Use of current computer models along with tools such as remote sensing and geographic information system (GIS) is a promising approach to better understand the impacts of removing residues on soil water conservation on different soils and geographical areas (Green et al. 2003).

15.10 RESEARCH NEEDS

The benefits of retaining crop residues on the soil surface, as with mulch tillage, for conserving soil water are widely recognized. Therefore, it is highly important that research involving crop residues be continued to develop practices for further enhancing soil water conservation, thereby improving crop production to help meet the food, fiber, and fuel needs for an ever-expanding world population. The need for improved soil water conservation is also important because the supply of fresh water, which is used by agriculture, is limited, and there is increasing competition for such water among agricultural, urban, industrial, and recreational users. Agriculture must do its part to conserve and efficiently use its share of the available water.

With regard to using water efficiently, research is needed to develop crops that have improved drought tolerance, are of greater commercial or economic value, and have improved resistance to insects, plant diseases, and climatic extremes (e.g., unseasonably low or high temperatures).

Another issue regarding soil water conservation as affected by mulch tillage pertains to the current interest in using crop residues to produce biofuel. Soil water conservation increases with increases in the amount of crop residues retained on the soil surface under many conditions. Considerable research has been conducted regarding the surface residue amount needed to control soil erosion, but such information generally is not available regarding soil water conservation. Therefore, it is highly important to conduct water conservation research under a wide range of conditions (crop residue levels, soils, cropping systems, climate, etc.) so that effective recommendations can be made for achieving optimum water conservation. With good results from a wide range of conditions, it should be possible to develop a model that could assist consultants, agency personnel, and/or producers to readily determine the amount of residues needed under prevailing conditions to achieve the desirable level of soil water required for obtaining a given level of crop production.

15.11 SUMMARY

Mulching, that is, maintaining organic or inorganic materials on or applying them to the soil surface, is an ancient practice. Through the years, however, clean tillage that incorporated crop residues and also controlled weeds became the norm. In fact, frequent and deep tillage was promoted also for conserving soil water. Such tillage conserved water, but resulted in soil aggregate breakdown, surface sealing, and excessive runoff, all contributing to serious soil erosion by water. Clean tillage also contributed to the disastrous soil erosion by wind during the major drought in the U.S. Great Plains in the 1930s. SMT, which undercuts the soil surface and leaves crop residues on the surface, was developed to help control erosion. It was soon found that retaining residues on the surface also provided for conserving soil water, and extensive research involving various types of mulch tillage subsequently has been conducted at numerous locations throughout the world. Soil water conservation generally increases with increases in the amount of residues retained on the soil surface.

Mulch tillage is possible with a variety of implements, but careful implement selection is essential to retain the optimum amount of residues on the surface to achieve soil water conservation and also to achieve effective weed control. Weed control under mulch tillage conditions (as well as with other tillage methods) received a major boost with the development of herbicides, beginning in the 1940s. Improved herbicides have been developed through the years and it is now possible to achieve complete weed control with herbicides and produce crops by the ultimate mulch tillage method, namely, NT, under many conditions. Through use of NT, most crop residues are retained on the soil surface, thereby providing the greatest opportunity for conserving soil water and subsequently achieving favorable crop production.

ABBREVIATIONS

CA	Conservation agriculture
G	Soil heat flux
H_{SOIL}	Sensible heat flux into the air
K_s	Surface saturated hydraulic conductivity
LE_{SOIL}	Latent heat flux
NT	No-tillage
R_{NS}	Reduced net radiation at the soil surface
SMT	Stubble-mulch tillage
SOC	Soil organic carbon
WSF	Winter wheat–fallow–grain sorghum–fallow

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16 Enhancing Precipitation-Use Efficiency in the World's Dryland Agroecosystems

G.A. Peterson, D.G. Westfall, and N.C. Hansen

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16.1 INTRODUCTION

Improving precipitation-use efficiency (PUE) in the world's dryland agroecosystems is more critical now than ever because the world's dependence on food produced in dryland areas continues to increase. Unger et al. (2006) expressed this global challenge clearly and succinctly:

> During the next several decades, dryland agriculture will play an increasingly important role in our efforts to maintain global food security. This is due to two relatively recent developments. The first is that, until about 1960, most increases in the world's food supply resulted from increasing the amount of land under production. Since then, most of the increasing demand for food in the world has been met by increasing yields. Additional lands still remain that could be brought into production, but as Evans (1998) pointed out, they tend to be unproductive, environmentally sensitive, remote, or otherwise unsuitable for agriculture. Indeed, many have argued that one of the most important reasons for continued yield increase is the need to protect environmentally sensitive land, including wildlife habitat.

> Furthermore, in many developed regions, including the United States, existing agricultural lands are gradually being lost due to such processes as erosion, salinization, urbanization (or "suburbanization"), and contamination.
>
> The second, and perhaps more alarming development, is that the world's supply of fresh water for irrigation is limited and increasingly the object of competition. Irrigated agricultural land, which constitutes less than one fifth of the world's arable land, has been the largest source of global yield increase for wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and other staple crops. Although there is now relatively little additional land left that is suitable for irrigation, a greater constraint in many regions is the availability of water for irrigation (Rothfeder 2001). Also, many large aquifers in the world already have been depleted to the point that remaining amounts of water are insufficient or pumping costs too great, for farmers to economically produce low value, bulk commodity crops. The world's most populous countries, China and India, are both depleting aquifers at alarming rates in order to feed their burgeoning populations. How, one must ask, are they to feed those populations when irrigation cannot keep pace with water demand?
>
> To meet this challenge, dryland cropping systems in developed and developing countries alike must use precipitation as efficiently as possible for food production. To realize increased efficiency requires an understanding of how crop production is related to such determining factors as precipitation and evaporative demand, water capture, water retention, and crop management.

What are "dryland agroecosystems?" They are often confused with "rainfed agroecosystems," an all-inclusive term, which is any agroecosystem that does not have irrigation. Dryland agroecosystems are a subset of rainfed agroecosystems, but where lack of precipitation limits crop and/or pasture production in part(s) of the year (Stewart et al. 2006). Dryland agroecosystems are found in climatic regions classified as semiarid and arid in many parts of the world, regions where annual evaporation potential E exceeds annual precipitation (P). These regions are further characterized by sporadic and highly unpredictable precipitation events accompanied by temperature extremes that create the potential for plant water stress during the crop cycle.

For example, in the North American Great Plains, potential E exceeds P during most months of the year, which significantly affects PUE by crop plants. About 75% of the annual precipitation in the North American Great Plains is received from April through September and is accompanied by high temperatures (Figure 16.1) and low relative humidity. Note that open pan evaporation tracks closely with the average air temperature (Figure 16.2), and thus the potential for evapotranspiration (ET) is high (Peterson and Westfall 2004).

It is important to realize that large differences exist among dryland agroecosystems of the world. The extremes can be illustrated by contrasting the North American Great Plains' temperate climate with two types of Mediterranean climate (Morocco and Oregon, U.S.) as shown in Figures 16.3 and 16.4 (Peterson and Westfall 2004). The Morocco and Oregon agroecosystems receive most of their precipitation in the coolest months of the year, which means they have smaller evaporative losses during the time they receive their precipitation relative to the Great Plains' environment.

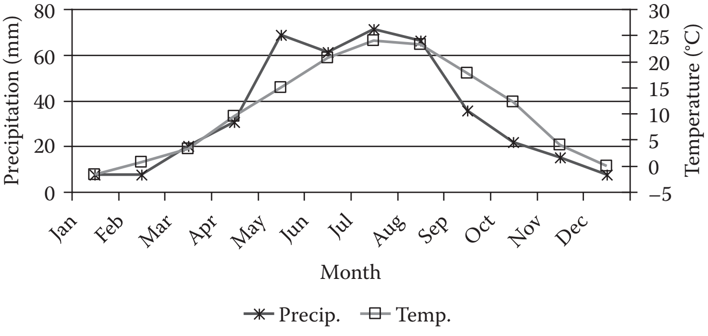

FIGURE 16.1 Long-term (1960–1990) precipitation and temperature distributions in eastern Colorado.

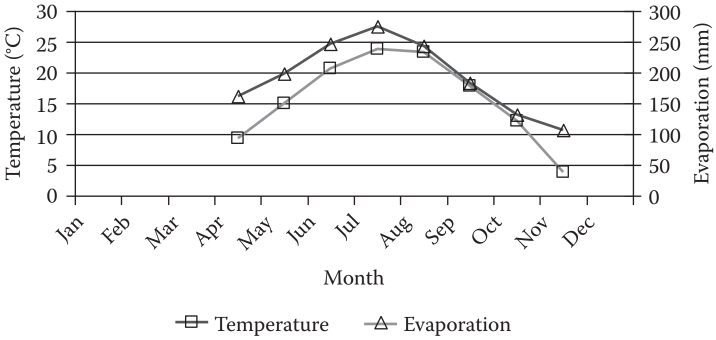

FIGURE 16.2 Long-term (1960–1990) temperature and open pan evaporation distributions for the summer growing season in eastern Colorado.

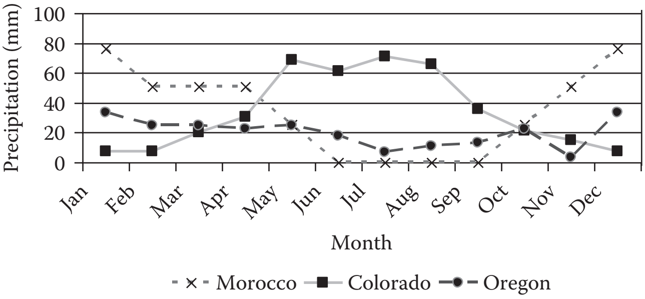

FIGURE 16.3 Long-term precipitation distributions in western Morocco (1934–2002), eastern Colorado (1960–1990), and eastern Oregon (1940–2002).

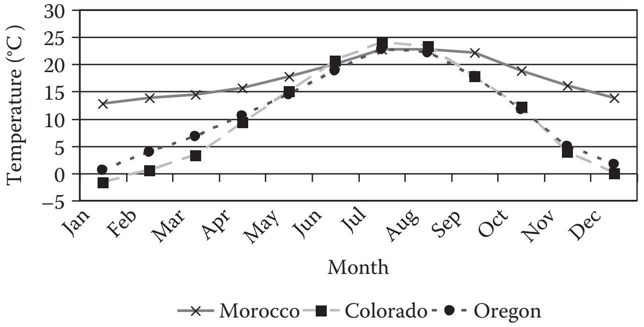

FIGURE 16.4 Typical temperature distributions in western Morocco (1934–2002), eastern Colorado (1960–1990), and eastern Oregon (1940–2002).

Also consider that air temperatures during the winter precipitation period in the Moroccan situation are 8°C–10°C warmer than in the Oregon situation. Water capture and retention issues differ greatly, even though both locations have Mediterranean climates. The contrast is heightened if one considers that snow management becomes an important issue in the Oregon environment, but not in Morocco. Precipitation distribution in relation to evaporation potential and other growing-season conditions dictate crop choices, crop sequences, and effectiveness of water conservation practices in any given climate.

Water availability is essential for plant establishment and successful production in all agroecosystems, especially in dryland systems. Dryland agroecosystems often have precipitation events that are short in length, high in intensity, and occur sporadically. Sporadic and intense precipitation events result in lower and less stable plant yields with more risk to the producers. Since precipitation in dryland agroecosystems is less reliable relative to rainfed agroecosystems, the risk of crop failure is higher. Successful crop production in dryland agroecosystems depends heavily on storing adequate soil water to sustain the crop until the next precipitation event. Thus, the focal point of the soil management practices in dryland agroecosystems is water conservation.

16.2 TILLAGE AND RESIDUE MANAGEMENT IN DRYLAND AGROECOSYSTEMS

Efficient precipitation management involves (1) maximization of precipitation capture in the soil, (2) minimization of stored soil water evaporation, and (3) maximization of plant water-use efficiency (WUE). Maximizing WUE involves proper variety selection, soil fertility, planting date, and a host of other management factors. Maximizing WUE of the plant is important to the ultimate system productivity, but it is of little consequence if one fails to capture the precipitation and retain it in the soil. Soil tillage and crop selection are the two primary tools available to manage precipitation storage in the soil. Reduced tillage or the complete avoidance thereof is the most effective approach to minimize evaporative soil water loss. Tillage choices, including type and timing, affect the amount of crop residue cover maintained on a soil surface and the soil pore size exposed to the atmosphere, which in turn control water capture and water retention.

The notion that maximizing water capture and minimizing evaporation is critical in dryland agroecosystems is not new, but only recently has the technology been developed to significantly change how the precipitation can be managed in dryland agroecosystems. Shaw (1911) and Widtsoe (1920), early in the twentieth century, recognized the principles of precipitation capture and retention, but the commonly accepted means of managing water in their era was tillage. Shaw (1911) stated: "The dominant idea in dry farming is in a sense two-fold. It seeks to secure to the greatest extent practicable the conservation and also the accumulation of moisture in the soil. To accomplish this end, the soil is stirred deeply, whether by the aid of the plow alone or by following the plow with the subsoiler, or by using some other implement, as the deep tilling machine. The ground is compressed subsequent to plowing, and a dust mulch is maintained upon the surface. The increase of organic matter in the soil is also sought." Widtsoe (1920) believed that water retention via dust mulching was the most important issue in dry farming, followed by its efficient use, but he could not effectively address water capture with the technology available to him. Shaw (1911) believed that water capture and retention were increased by more and deeper plowing, thinking it would increase storage capacity of the soil. Neither of these early researchers had any concept of crop residue retention and soil protection; tillage, as they recommended, often led to extensive soil erosion because of bare soil surfaces. Modern research has clearly demonstrated that intensive tillage has many adverse effects on the soil, including losses in soil organic matter (SOM). Careful management of crop residue via reduced and no-till (NT) technology allows us to more effectively and simultaneously address water capture and retention, as well as soil conservation (Unger et al. 2006). Soil management with reduced and NT systems has resulted in more sustainable dryland agroecosystem production.

Recognizing the relationships between climate and tillage is critical for efficient precipitation management. This chapter discusses the principles of managing dryland production scenarios from a systems perspective. Before specific climate and tillage interactions are explored, however, it is important to review the principles that govern precipitation capture and retention in the soil reservoir. Once these are understood, the reader should be able to address management issues in a wide range of dryland environments.

16.3 PRECIPITATION MANAGEMENT PRINCIPLES

16.3.1 Precipitation Capture in the Soil

The first step in water conservation in dryland agroecosystems is capturing the incident precipitation, whether it is from rain or snow. System sustainability depends on water capture maximization within the economic constraints of the system (Unger et al. 2006).

At first glance, water infiltration into soil appears to be a relatively simple process with water entering and simply displacing the soil air. It is more complex, however, because it involves both saturated and unsaturated water flows. Unsaturated flow is driven primarily by the attraction of water to dry solid surfaces (adsorption) and the surface tension of water held between the solids (capillarity). Together, adsorption and capillarity produce the matric potential energy state of water. So when the precipitation intensity is below the saturated flow rate of the soil surface layer, the water intake is governed by the unsaturated flow. As soon as the water application rate exceeds the soil's unsaturated intake rate, saturated flow is the dominant process (Unger et al. 2006).

Water entry rate under saturated conditions, the so-called infiltration rate, is controlled by surface soil porosity, soil water content, and soil profile permeability. Water capture is complex because the maximum infiltration rate occurs at the beginning of a rainfall event and decreases rapidly as water fills the surface pore space. The dry soil has a large storage capacity and a large potential energy gradient at the wetting front relative to the same soil in a uniformly moist condition. As the wetting front advances, the gradient and infiltration rate decline.

Water infiltration rates for a given landscape also can differ for reasons that are not subject to management, like soil texture. Surface soil macroporosity, a desirable soil property for rapid water infiltration, is highly governed by soil texture. Fine-textured soils generally have less macropore space and, consequently, lower infiltration rates than coarse-textured soils. Surface soil aggregation also regulates macropore space; soils of the same texture, but with different degrees of aggregation, can differ greatly in the amount of macropore space. Fortunately, the degree of soil aggregation can be altered by soil management practices. For example, increasing the SOM content and decreasing the tillage intensity can improve soil aggregation and in turn improve water infiltration rate. Management practices that improve soil structural stability, for example, those that increase SOM content, can help improve the infiltration rate. By contrast, soils with weak structure can quickly lose their ability to absorb water as the surface aggregates disintegrate and surface pore spaces become smaller. This can occur upon wetting and from raindrop impact.

Management of soil cover through tillage is a primary factor in improving water capture in dryland agroecosystems because of the soil aggregate protection it provides. The advent of herbicidal weed control created new scenarios for soil cover management, and there is the possibility of retaining much of the previous crop's residue on the soil surface.

Soil cover is defined as the sum of canopy cover and crop residue cover. Soil cover is highly dynamic and can range from 0% to 100%, all within a growing cycle of a crop, depending on the cropping and tillage system being used (Unger et al. 2006). For example, at planting, the soil cover consists only of the previous crop residue component. As the new crop grows, the cover becomes increasingly dominated by the plant canopy. Meanwhile the residue component is in decline as microbial decomposition and physical deterioration occur. When the crop matures and the canopy dies, residues once again become the primary soil cover. Crop cultivation during the growth period also influences the total cover at a given point in the cycle.

Residue cover or crop canopy cover over a soil protect soil aggregates from raindrop impact energy. Surface soil structure that has no cover is easily damaged by raindrops because the raindrop energy causes soil particles to "slake" from aggregates, thus leading to their destruction; thus, the surface soil macroporosity is degraded. Soil water content affects how easily the aggregates slake; wetter soil slakes more readily. The ultimate result of soil aggregate slaking is a crusted soil surface after the rainfall event, which has little macroporosity and hence a very low water infiltration rate.

When crusting occurs, tillage is needed to break the crust, creating macroporosity and thus allowing water from the next precipitation event to infiltrate. However, tillage increases the evaporation rate by exposing moist soil to the dry atmosphere, thereby causing a net water loss. Thus, there is a negative feedback loop where tillage creates a soil surface prone to crusting, which requires additional tillage for water capture. The frequent tillage gradually degrades SOM and soil structure, making the soil surface even more vulnerable to crusting. It is best to avoid crust formation, thereby eliminating the need for tillage. Crusting can be minimized by protecting the soil surface with residues and/or crop canopy cover.

A plant canopy can intercept up to 45% of the raindrops (Troeh et al. 1991), which means that the plant leaves are absorbing the drop energy and the water drips to the soil surface with greatly reduced impact, resulting in less soil aggregate damage; the surface soil pores remain open. As the leaf area index increases during the growing season, the ground cover increases, which further decreases the raindrop energy impact on the soil surface. Unger et al. (2006) stated that "Benefits in water capture resulting from canopy development are greatest in areas with summer precipitation; for example, corn (*Zea mays* L.) or grain sorghum (*Sorghum bicolor* (L.) Moench) production cycles in the Great Plains of North America occur during a period when 75% of the annual precipitation is received. By contrast, dryland areas that receive primarily low-intensity winter precipitation, like the Pacific Northwest in the United States, do not have active canopy development during the period when most of the precipitation is received. Early establishment of fall-sown crops to obtain partial soil cover also is recognized as an important deterrent to soil detachment and runoff during winter months."

Crop residues can protect soil aggregates from raindrop impact and destruction just as crop canopies do. Crop residues play a highly beneficial role in dryland agriculture by protecting the soil against erosion by wind and water and decreasing the soil water evaporation rate. They also have competing economic roles such as providing animal fodder and/or as a fuel source. Obviously, the latter roles are not independent of the others.

When available in sufficient amounts, residues can physically block water runoff and slow the evaporation rate after a rain event, thus allowing water to move into the profile before being lost by evaporation. The water and energy balances of residue-covered soils constitute complex processes and the amount of water conserved by the residues varies with specific circumstances (Papendick and Campbell 1988).

Tillage practices greatly alter the amount of residue cover on a soil surface. Tillage is practiced for reasons ranging from weed control to seedbed preparation and often these operations influence soil water capture by their disruption of soil crusts and alterations in surface aggregate size distribution. Tillage operations are never independent of crop residue cover because even the most minimal soil disturbance tends to incorporate some residues, which decreases the cover on the soil surface (Unger et al. 2006). Most often tillage creates large open macropores at the soil surface that greatly increase the initial water infiltration rate. If a soil has little cover, the aggregate sizes decrease during rainfall events and the infiltration rate decreases in proportion to the rainfall intensity and duration due to macropore destruction. Tillage management choices can alter water capture, but they are not independent of the tillage effects on the residue cover. Ideally, a large amount of soil macroporosity, with at least 50% soil cover, should result in a high infiltration rate that is sustainable throughout a rainfall event. Jones et al. (1994) illustrated this principle; they reported higher infiltration rates and lesser amounts of runoff with stubble-mulch tillage than with NT management. Reduced tillage minimizes crust formation, preventing the need for additional tillage. The increased organic matter at the soil surface improves aggregation and further improves infiltration. This positive feedback loop is ultimately more sustainable that a system dependent upon frequent tillage.

Soil structure deteriorates with increasing tillage intensity and/or years of cultivation. Tillage has negative effects on soil aggregates for two main reasons: (1) physical grinding that reduces aggregate size and (2) increased SOM oxidation that occurs because of macroaggregate destruction and subsequent increased exposure of organic compounds to soil organisms. As aggregate size distributions shift to smaller diameters, microporosity increases at the expense of macroporosity, which eventually results in decreased water infiltration rates. Implementation of reduced and NT systems has the potential to reverse the effects of excessive tillage over the long term.

16.3.2 RETENTION OF STORED SOIL WATER

After precipitation has been captured in the soil, it must be retained for subsequent use by a crop. Successful retention involves reducing the losses due to evaporation and transpiration by weeds. Some intercepted quantities of precipitation evaporate from the canopy and residue cover before they can be stored in soil; but even after water is stored in the soil, it is very susceptible to evaporative loss. Evaporation occurs both before a crop is planted and during a crop's growing season. Losses before planting are especially critical because they reduce the amount of water available for the ensuing crop and may also affect crop establishment.

Soil water evaporation rate occurs in three stages (Hillel 1998; Lemon 1956). First-stage evaporation depends on the net effect of environmental conditions (wind speed, temperature, relative humidity, and radiant energy). The evaporation rate decreases rapidly during the second stage when the water content in the soil decreases; at this point, the evaporation rate depends mainly on the soil conditions that control water flow to the surface. During the third stage, when water is moving to the surface as vapor, the evaporation rate is low and controlled mainly by the adsorptive forces at the solid–liquid interface (Hillel 1998; Lemon 1956). The greatest potentials for decreasing evaporation lie in the first two stages of evaporative water loss from a soil system.

The soil water evaporation process is a highly complex process because it involves water flow in the soil in response to water potential differences, soil temperature gradients, and atmospheric conditions. Evaporation is greatest when a soil is wet and the air is dry (low humidity or vapor pressure). The soil water potential changes constantly in response to the decreases in water content due to evaporation, use by plants, or deep percolation and increases due to precipitation. As a soil dries at the surface, water must flow to the surface to replenish the loss by evaporation. With continued evaporation, the flow distance increases, which results in increasingly slower flow rates to the surface as liquid or vapor, resulting in lower rates of evaporation. Eventually, water flow is only in the vapor phase, which results in even lower evaporation rates. These constantly changing water potential conditions result in constant changes in the water flow rate to the surface. The water potential of air also changes constantly due to climatic changes. The evaporation cycle restarts each time water is added to the soil, by precipitation (Unger et al. 2006).

Many practices have been evaluated regarding their effect on soil water evaporation. Effective practices to reduce evaporation form a barrier to prevent vapor movement from the soil, negate the energy available for evaporation, minimize the vapor pressure gradients at the soil–atmosphere interface, or disrupt water flow within the soil. Mulch cover on the soil surface is the most effective and practical method of reducing evaporative losses from the soil. A mulch is "any material such as straw, leaves, plastic film, loose soil, etc., that is spread or formed upon the surface of the soil to protect the soil and/or plant roots from the effects of raindrops, soil crusting, freezing, evaporation, etc." (SSSA 1997). This chapter limits discussion to the effects of straw (crop residues) and loose soil on soil water evaporation.

Crop residues are plant materials (straw, stover, stalks, leaves, cobs, etc.) remaining after harvest of a crop for its grains, lint, etc. In many areas of the world, these materials have little economic value and remain in the fields after harvesting the crops (Unger et al. 2006). However, straw, stover, etc., are used in some cultures as feed for animals, fuel, manufacturing, or shelter (Parra and Escobar 1985; Powell and Unger 1998), which produces a competitive environment for the materials. There are numerous competitive uses for residues, but the discussion will be confined to their value for controlling evaporation.

Crop residue characteristics that affect evaporation are their orientation (standing, flat, or matted), which affects the thickness and porosity of the layer; layer uniformity; reflectivity, which affects the radiant energy balance at the surface; and the aerodynamic roughness resulting from the residues (Van Doren and Allmaras 1978).

Smika (1983) measured soil water losses that occurred during a 35-day period without precipitation. Soil water loss was 23 mm from bare soil, 20 mm with flat wheat residues, 19 mm with 75% flat and 25% standing residues, and 15 mm with 50% flat and 50% standing residues on the surface. Nielsen et al. (1997) showed that the potential evaporation decreased as the residue height increased. Height was especially important when stem populations were <215 stems per square meter, and the effect decreased with increasing stem populations. Smika (1976) measured soil water contents 1 day after a 13.5 mm rain and again at 34 days without additional rain. Initial soil water contents were similar to a depth of 15 cm where conventional-, minimum-, or no-tillage treatments were imposed after harvesting winter wheat. The treatments resulted in surface residue amounts of 1.2, 2.2, and 2.7 Mg/ha, respectively. At 34 days, the soil water content was <0.1 m^3/m^3 to depths of 12 cm with conventional tillage, but only to a depth of 9 cm with minimum tillage. By contrast, under NT, the soil had only dried to a 5 cm depth. Total water remaining in the soil was greatest under NT management, where the surface residue amount was also the greatest.

The data reported in the foregoing studies clearly show that crop residue mulch retained on the soil surface can reduce soil water evaporation and thereby conserve water for crop use. The evaporation reductions in these cases result primarily from reduced turbulent transfer of water vapor to the atmosphere.

A major limitation to using residues as a mulch in dryland agroecosystems is that sometimes the cropping systems do not produce enough residues and resultant soil cover to have a significant effect on evaporation. In some cases, virtually no residues remain on the surface because they are removed for fodder or fuel. Under such conditions, other means of controlling evaporation have been investigated. These generally involved reducing capillary water flow to the soil surface, which can be achieved by tillage at a shallow depth. This practice is known as dust mulching (also soil mulching) and is a form of clean tillage (Unger et al. 2006). Dust mulching can reduce evaporation, but it is most effective where a distinct rainy season is followed by a distinct dry season or where water moves to the surface from deeper soil layers or a water table (Papendick et al. 1973; Papendick and Miller 1977).

However, dust mulching leaves soils vulnerable to erosive forces. When considering overall soil management of precipitation capture, water retention, and soil erosion control, it is best to keep cover on the soil and not rely on dust mulch.

Another major issue in retaining stored soil water is minimizing water use by weeds. Soil water use by weeds must be avoided or minimized to obtain optimum soil water storage at crop planting time. Weeds present before planting decrease the soil water supply for later use by the crop and those present during the growing season compete directly with the crops for the available water supply. Weed control can be achieved by tillage alone, herbicides alone, or a combination of the two methods. Crop rotations also are a management tool for reducing weed pressure (Wiese 1983). Regardless of the control method used, timely weed control is essential because weeds may use as much as 5 mm of soil water each day (Wicks and Smika 1973). When tillage is used, a balance is needed between water use by developing weeds and that lost due to exposing moist soil to the atmosphere. Because water loss after each tillage operation may amount to 5–8 mm (Good and Smika 1978), the decision about when to till for weed control is not an easy one, and it must be made by the individual manager for a given situation. Herbicidal weed control is the most water-efficient approach because no additional water is lost from the soil by tilling and the crop residue is not disturbed.

Hand weeding is commonly practiced by small-scale farmers in many countries, such as those in sub-Saharan Africa (Twomlow et al. 1997). As with tillage, repeated weeding by hand may be needed. In Zimbabwe, for example, WUE and grain yields were greater when weeding for corn was at 2, 4, and 6 weeks after emergence than with a single weeding at 2 weeks after emergence. The soil was driest and the yields were lowest when the weeds were not controlled.

Cover crops can be grown to protect the soil against erosion, especially in places where residue production is low and adequate water for such crop is available. Although such crops are not considered to be weeds, their effect on soil water conservation is essentially the same as that of weeds. Cover crops may have beneficial effects such as soil erosion reduction and improved water infiltration, but they also use water. In most cases, growing cover crops in dryland agroecosystems decreases the total water available to the subsequent crop, and thus this practice is usually not recommended. There are specific climatic situations where the use of cover crops may be of value and the reader can learn more about those cases in Unger et al. (2006).

16.4 APPLICATION OF WATER CAPTURE AND RETENTION PRINCIPLES IN A SYSTEMS CONTEXT

To gain a perspective of how to best manage precipitation capture and to maximize PUE, the west central Great Plains of North America is herein used as a test case. Dryland agriculture in the west central Great Plains was developed around wheat production in a wheat–fallow agroecosystem. The wheat–summer fallow system was developed and adopted to decrease the risk of crop failure (Peterson et al. 1996). The soil water stored during the summer fallow period increases the probability of a successful wheat crop. Spring wheat is grown in the northern Great Plains and is planted in late spring (March) with a late summer harvest (August). The fallow period varies in length from 18 to 21 months, depending on the exact planting and harvest dates. The actual time the wheat plants are growing in the field is only 3–6 months out of the 24-month cycle for spring wheat and about 10 months for winter wheat. Weed control during the fallow period in both the spring and winter wheat regions is critical because maximum water storage can only occur if the fields are weed-free. Prior to the advent of herbicides, the only feasible weed control was tillage, which usually left the soil surface barren of residue cover. Following the 1930s Dust Bowl era, summer fallow became a way of life for the farmers in the west central Great Plains. Higher crop prices during and after World War II and much improved tractor power systems and implements facilitated tillage for weed control during the fallow period (Greb 1979). Haas et al. (1974) estimated that there are more than 6.1 million hectares (Mha) of summer-fallowed land in the U.S. Great Plains alone, and since the Canadian provinces also use the summer fallow technique, the total area was even larger. In 1979, Greb chronicled the progress in soil water storage efficiency in winter wheat–fallow systems from the early 1900s through to 1977 and then projected progress through 1990 (Table 16.1). Over time, changes in fallow tillage systems have improved water storage, fallow efficiency (% of fallow precipitation stored as soil water), winter wheat yield, and PUE. As tillage type changed, the number of tillage operations per fallow period decreased, and the amount of crop residue remaining on the soil surface increased. PUE doubled from 1916 to 1975, increasing from 1.22 to 2.78 kg of wheat/ha mm of precipitation. This was largely due to improved fallow-period soil water storage efficiencies, which increased from 19% to 33% over the same time period. Greb (1979) predicted that fallow efficiency would increase to 40% by 1990, resulting in a PUE of 3.25 kg/ha mm. The mechanisms that allowed the improvements in fallow efficiency and PUE are a complex array of interacting factors that were reviewed earlier in the chapter. In summary they include (1) maintained water infiltration rates because the residue cover absorbs raindrop impact energy, thus protecting the soil aggregates; (2) decreased first-stage evaporation rates due to cooler soil temperatures under the residue; (3) reduced opportunity for stimulated evaporation due to fewer tillage events; (4) decreased wind speed at the soil surface because of residue protection; (5) improved fertilization practices; (6) increased opportunity for weed control; (7) improved semidwarf wheat cultivars; and (8) increased timely fallow operations because of more tractor horsepower and better equipment (Peterson et al. 1996). No single factor has changed the system, but all have worked in concert to create a net positive outcome.

TABLE 16.1
Progress in Fallow Systems and Winter Wheat Yields, U.S. Central Great Plains Research Station, Akron, Colorado

Years	Changes in Fallow Systems	Number of Tillages	Fallow Water Storage[a] (mm)	Fallow Efficiency[c] (%)	Winter Wheat Yield (kg/ha)	Precipitation Use Efficiency (kg/ha mm)
1916–1930	Maximum tillage; plow harrow (dust mulch)	7–10	102	19	1070	1.22
1931–1945	Conventional tillage; shallow disk, rod weeder	5–7	112	24	1160	1.43
1946–1960	Improved conventional tillage; begin stubble mulch 1957	5–7	137	27	1730	2.06
1961–1975	Stubble mulch; begin minimum tillage with herbicides (1969)	2–4	157	33	2160	2.78
1976–1990	Projected estimate; minimum tillage; begin no-till 1983	0–2	183[b]	40	2690	3.25[c]

Source: Adapted from Greb, B.W. Reducing drought effects on croplands in the west-central Great Plains. USDA Information Bulletin No. 420, 31 pp. U.S. Govt. Printing Office, Washington, DC, 20402, 1979.

[a] Based on 14-month fallow, mid-July to second mid-September.

[b] Assuming 2-year precipitation per crop in a wheat–fallow system.

[c] Fallow efficiency = soil water stored during fallow/precipitation received during fallow period.

16.4.1 MODERN SOIL WATER STORAGE POTENTIAL IN FALLOW

As is observable in Table 16.1, Greb (1979) predicted increased fallow storage efficiency based on improved residue management and more economical NT methods. Yet, it has not been possible to improve upon the 35% storage efficiency that Greb achieved in the early 1970s. Fallow efficiency reports from the 1980s and 1990s are generally less than 40%, regardless of the climatic zone where the data were collected (Table 16.2). The range of efficiencies reported by McGee et al. (1997) in Colorado under NT conditions, 17%–28%, are disturbingly low. These data represent a wide range of climate and soil combinations, and it appears it will be difficult to improve upon fallow efficiency with the current fallow technology. Fallow storage efficiency was equally low in the northern climates of Canada and North Dakota, despite their lower evaporation potentials. Their much longer fallow period, 21 months for spring wheat–fallow systems compared with 14 months for winter wheat–fallow systems, also contributes to the low efficiencies in the region with lower evaporation.

Greb et al. (1967) and Unger (1978) demonstrated that surface residue greatly increases fallow water storage, but that residue amounts in excess of 6 mg/ha are required to achieve fallow efficiencies greater than 35%–40%. Unfortunately, the residue amounts in the west central Great Plains at wheat harvest, the maximum residue accumulation point in the system cycle, are commonly in the 2.2–5.6 mg/ha range. With favorable precipitation they can reach 7 mg/ha, and on soils that receive runoff water from surrounding hills, the residue levels may even reach 10 mg/ha; but the latter cases are rare. Since the residue levels in the west central Great Plains area usually do not reach the 6 mg/ha threshold, it is highly likely that the projected fallow efficiency of 40% (Greb et al. 1967) will not be achieved.

TABLE 16.2
Modern Soil Water Storage Efficiencies of No-Till and Reduced Till Summer Fallow Systems over a Range of Environments in the Great Plains of the United States

Water Storage Efficiency (%)			
Range	**Range**	**State or Province**	**Reference**
18[a]	—	Saskatchewan, Canada	Campbell et al. (1987)
31[a]	(26–36)	North Dakota	Deibert et al. (1986)
37[a]	32–42	Montana	Tanaka (1989)
49	—	Colorado	Smika (1990)
22	17–28	Colorado	McGee et al. (1997)
25	10–37[b]	Kansas	Schlegel (1990)
30	25–35	Kansas	C.A. Norwood[c]
10	—	Texas	Jones and Johnson (1993)

Source: Peterson, G.A., Schlegel, A.J., Tanaka, D.L., and Jones, O.R., *J. Prod. Agric.*, 9, 180–186, 1996.

[a] Spring wheat (21-month fallow), all other data for winter wheat (14-month fallow).

[b] Reduced tillage.

[c] Personal communication, Southwest Kansas Research Center, Kansas State University, Garden City, Kansas.

16.4.2 MANAGEMENT AND WATER STORAGE INTERACTIONS

When the residue amounts are too small to allow further reductions in evaporation rates and totals, other approaches must be found for increasing PUE. The challenges are (1) to increase water capture, (2) to decrease the water storage time in the soil, and (3) to choose plant species and rotations that use water more efficiently.

Water capture and storage efficiency are usually greatest when the soil surface is dry and in a receptive condition for rainfall. At wheat harvest time in the Great Plains (July), soils often are at zero plant available water content and can absorb water rapidly. At this point in the crop cycle, there is maximum residue cover on the soil; thus, the soil conditions are very receptive to water infiltration.

Smika and Wicks (1968) reported that substituting herbicidal weed control for tillage greatly improved water storage during the early portion of the fallow period in a winter wheat system. Conventional plow tillage treatments stored no water in the early fallow period, while minimum tillage treatments stored 12% of the precipitation and NT increased the water storage efficiency to 24%. By spring of the following year, which is only 8 months into the 14-month fallow period, the plow tillage had stored only 16% of the precipitation (56 mm of water), while the minimum till and NT systems had stored 40% (140 mm of water) and 60% (210 mm of water), respectively.

When water is stored early in the fallow season, the storage becomes less efficient in the latter part of the fallow period. For spring wheat–fallow systems, Haas and Willis (1962) also found that little or no soil water was stored in summer fallow after July 1. These data point to the possibility of terminating the fallow period, in NT and reduced tillage systems, before July, which will permit the planting of a summer crop to use the water via transpiration rather than lose it by evaporation.

Management techniques that foster early water capture and retention after wheat harvest and during the winter and spring periods usually result in moist surface soils that are near field capacity by May. When a rain event occurs in the summer period, as shown in Figure 16.1, the greatly reduced infiltration rates allow water to remain on the NT soil surface for longer periods compared with tilled conditions. The high temperatures in the late fallow period from July to September, in concert with high vapor pressure deficits in the air, accelerate evaporation and keep precipitation capture to a minimum. On sloping land, runoff is increased by the compact soil surface and water capture is decreased even more than on level land (Jones et al. 1994).

In conventional winter wheat–fallow systems, where weeds are not controlled after harvest and/or tillage is used for weed control, the soil water contents in spring are much lower and the water storage potential during the May–September period is greater than in NT systems. Since these soils are tilled multiple times for weed control during the fallow period, they have more macroporosity at the surface and water infiltration is not impeded. However, any water stored in the tillage layer is rapidly lost by evaporation because the fallow weed control tillage hastens evaporation by exposing moist soil during the hottest period of the year.

Reports by Black and Power (1965), Deibert et al. (1986), and Norwood (1994) all substantiate the inefficiency of water storage in NT wheat–fallow systems during the latter portion of the summer fallow period, whether it is a winter or spring wheat production system. In early NT research, Black and Power (1965) working with a spring wheat–summer fallow system found that the fallow storage efficiency from harvest to the following May was 66%, from May to September was 9%, and from September to seeding the next spring was 19%. Deibert et al. (1986) working with spring wheat–summer fallow systems reported early fallow storage efficiencies of 56%–59% (90–125 mm of water stored), but efficiencies of only 26%–36% after a full 21-month fallow period (112–117 mm of water stored). Norwood (1994) in Kansas reported a storage efficiency of 46% for the 11-month period from winter wheat harvest to spring sorghum planting (175 mm of water stored). Norwood's wheat–summer fallow system, for the entire 14-month fallow period, only had an efficiency of 23% (137 mm of water stored). There was a 38 mm water loss during the late fallow period. A long fallow period appears to decrease the amount of stored water under most dryland production systems.

Most data indicate that there can be as much or more stored water in NT-managed soils in the spring after wheat harvest, as there will be if fallow is continued until fall wheat planting in September. It appears that intensifying the cropping pattern, by shortening the summer fallow period and using the precipitation nearer to the time it is received, would increase the overall system PUE and ultimately increase the soil productivity via the increased annual amounts of residue added to the soil.

16.4.3 TESTING THE HYPOTHESIS

Peterson et al. (1993) established a long-term agroecosystem project in 1985 to test the hypothesis that it was possible to decrease the length of the fallow period by using NT techniques and that more intensive cropping systems could be successful. Specifically, they were looking for ways to reduce the amount of summer fallow time and to reverse the soil degradation that has occurred because of the tilled wheat–fallow cropping system.

The experiment had three variables: (1) climate regime; (2) soils; and (3) management systems (Peterson et al. 1993). The climate variable was based on three locations with varying levels of potential evapotranspiration; the soil variable was achieved using a soil catena with three distinct soils at each site; their management system variable was increasingly intensive cropping systems ranging from wheat–summer fallow to continuous cropping. The system responses were assessed via total aboveground plant productivity, WUE, changes in the soil chemical, physical, microbiological properties, and economic evaluations. All soil samples, dry matter yields, soil water measurements, etc., were collected from the benchmark areas within each experimental unit, and the details are reported in Peterson et al. (1993). It was possible to decrease the length of the fallow period by using NT techniques, and the more intensive cropping systems could be successfully used (Peterson and Westfall 2004). In fact, cropping systems were successfully intensified across the entire climate gradient included in their experiment; annualized grain yields increased by more than 75% relative to the yield of the wheat–fallow system. The largest step gain in annualized yield was achieved with the addition of maize or sorghum to the system (two crops in a 3-year system). Increasing cropping intensity to the 4-year system (three crops in 4 years) only resulted in small yield increases relative to the 3-year system. Net income for farmers increased from 25% to 40% relative to the traditional wheat–fallow system.

They also tested a continuous cropping system that included annual forage crops. Yields of total aboveground biomass were used to compare the continuous cropping system with the systems containing only grain crops. Continuous cropping produced annualized total biomass yields superior to all systems containing fallow. Avoiding a fallow year maximized total aboveground biomass production. However, the monetary value of the forage crop in their continuous systems was so low that the continuous cropping system was not as profitable as the 3- or 4-year grain crop systems that included a summer fallow period (Peterson and Westfall 2004).

They were able to determine that systems with fewer summer fallow periods increased WUE; the 3-year system had a 27% increase in grain WUE relative to wheat–summer fallow, and the 4-year system had a WUE 37% greater than that of wheat–summer fallow. Crop use of stored soil water that was usually lost by evaporation in a wheat–summer fallow system was responsible for the increased grain and biomass yields in the more intensive rotations, which resulted in the increased WUE.

Peterson et al. (1993) also had hypothesized that reducing the amount of summer fallow time would help reverse the soil degradation, especially the weak soil structure that has resulted from many years of tillage and less amounts of crop residue return in the typical wheat–fallow cropping system. Residue return is particularly low in a wheat–fallow system because a crop is produced only once in every 2 years. Weak, unstable soil structural units reduce the receptivity of the soil surface to water infiltration. Soils in dryland farming areas are usually low in SOM because they were formed in semiarid environments where only small amounts of vegetative carbon were returned to the soil for potential storage. Despite this condition, these soils often had good aggregate strength when first placed under cultivation. In the Great Plains of North America in particular, the native grass vegetation, with its highly developed fibrous surface root system, provided a well-structured soil that allowed pioneer farmers to do a good job of water capture within the limits of the technology of their era. Since all of the cropping systems relied on frequent tillage events, the soil organic C (SOC) depleted rapidly and the aggregate size and strength diminished quickly. Surface crusting began to occur after the rainfall events and the farmers' only alternative was more tillage to create macropores to improve the water capture potential of the next precipitation event. Thus, both water capture and retention capabilities have declined with time. Peterson and Westfall (2004) reported that NT management practices, coupled with cropping intensification, did begin to reverse the negative effects of past management. Properties of the immediate surface soil layer (2.5 cm), such as bulk density, porosity, and macroaggregation, affect the pore space and pore size and thus are useful indicators of changes in water capture potential.

Cropping system intensification under NT management decreased the bulk density of the surface soil layer (Shaver et al. 2002). For example, continuous cropping decreased the soil bulk density from 1.32 g/cm^3 in the wheat–summer fallow system to 1.22 g/cm^3. This reduction in the bulk density resulted in an increase of 0.04 m^3/m^3 in the total porosity, meaning that there is 4% more space to infiltrate water from a rainfall event. Furthermore, there was an absolute increase of 5% in effective pore space, which means that even if the surface soil is at field capacity water content, there is 5% more space to accommodate water from a rainfall event. The improvements in surface soil porosity were related to an increase in the proportion of macroaggregates relative to microaggregates (Shaver et al. 2002).

In the Great Plains environment, rapid water intake during and after a rainfall event is critical because water that ponds on the soil surface, for even a short time, is rapidly evaporated. Improvements in macroaggregation and effective porosity thus increase the opportunity for more efficient water capture.

The causal agent for the improvement in the physical properties was the addition of more crop residue biomass and less soil stirring (tillage) in the more intensive cropping systems relative to the wheat–fallow system (Shaver et al. 2003). Coupled with the lack of soil disturbance in an NT environment, the additional residue carbon promoted aggregation and increased aggregate stability. SOC levels increased after only 12 years of intensively cropped NT management (Sherrod et al. 2003). Each step of increased cropping intensity tended to increase the surface SOC at all soil depths, but the increases were most significant in the surface 0–2.5 and 2.5–5 cm soil layers. Continuous cropping, with no summer fallow period, increased the organic C content of the surface 0–2.5 cm of soil by 39% relative to wheat–fallow. The SOC increases were closely associated with the changes in physical properties reported by Shaver et al. (2003). Furthermore, the increases in soil C were directly linked to increased crop residue biomass returned to the soil over the 12-year life of the experiment (Shaver et al. 2003).

Peterson and Westfall (2004) concluded from their long-term agroecosystem experiment (Peterson et al. 1993) that NT technology has greatly altered our ability to manage precipitation in dryland systems. Specifically, it improved the potential for precipitation capture and for soil water retention. In turn, the improved precipitation capture and the retention permitted increased the cropping intensity, which has proven to be both agronomically and economically sound in the west central Great Plains of North America. Furthermore, these management strategies have provided positive feedbacks to the soil system that should improve long-term productivity. Positive feedbacks included increased SOC levels that improved surface soil structure, which in turn has increased the water infiltration rates of the soils. Increased water capture because of greater infiltration has the potential to increase PUE by providing more water for plant production and additional crop residue return to the soil. Greater season-long cover over the soil, whether it be crop canopy or crop residue, and higher water infiltration rates all have major impacts in decreasing soil erosion by wind and water.

16.4.4 Principles and Inferences

Farahani et al. (1998) provided an insightful dissection of the fallow period in an NT winter wheat–summer fallow system common in the west central Great Plains. It has proven to be very instructive in terms of how we might best maximize the PUE for a particular agroecosystem. Using soil water storage data from their long-term experiment in the Great Plains of North America, they divided the 14.5-month summer fallow period into three stages (Figure 16.5). Stage I is the first 2.5-month period after wheat harvest until mid-September; Stage II is the next 7.5-month over winter period

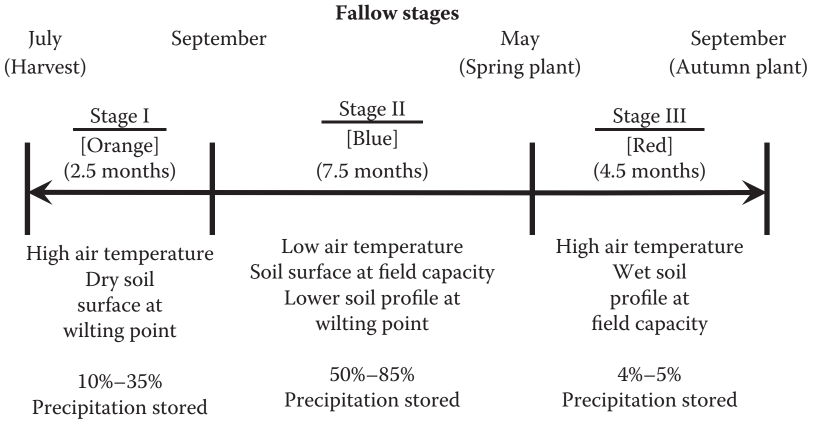
Fallow stages
July
(Harvest)
September
May
(Spring plant)
September
(Autumn plant)
Stage I
[Orange]
(2.5 months)
Stage II
[Blue]
(7.5 months)
Stage III
[Red]
(4.5 months)
High air temperature
Dry soil
surface at
wilting point
10%–35%
Precipitation stored
Low air temperature
Soil surface at field capacity
Lower soil profile at
wilting point
50%–85%
Precipitation stored
High air temperature
Wet soil
profile at
field capacity
4%–5%
Precipitation stored

FIGURE 16.5 Fallow stages and their characteristics for dryland cropping systems in eastern Colorado.

from fall to early May; and Stage III is the 4.5-month late fallow period from spring until wheat planting in mid-September. Their partitioning strategy was not arbitrary; each stage coincided with a combination of soil water and air temperature conditions. They coded Stages I, II, and III as "orange," "blue," and "red" zones to depict the water storage potential of each stage. Note that the various crop and noncrop phases of 3- and 4-year systems also fit well with these periods.

Water storage efficiencies are greatest (50%–85%) in the "blue" zone because air temperatures are lowest and precipitation is received as snow and/or low-intensity storms (Figure 16.5). Storage efficiency in the "orange" zone is much lower (10%–35%) because air temperatures are much higher during this stage. However, surface soil conditions are dry (near wilting point), and thus some water infiltrates before it is lost by evaporation. Rainstorm intensity governs whether one is at the low or high end of the range. The "red" zone has high air temperatures (similar to the "orange" zone), but surface soil and profile water contents are near field capacity, evaporation is high, and no water is stored during this time period. These fallow period stages can be used to determine what has changed as cropping systems are intensified and can give us insight into what might be feasible for future improvements.

Their analysis of the cropping systems revealed that switching from a 1 crop in 2-year system, such as wheat–summer fallow, to a 2 crops in 3-year or 3 crops in 4-year system did not appreciably change the proportion of time in total fallow (Table 16.3). In fact, the proportion of time in fallow (no crop in the field) actually increased as the cropping was intensified, while the proportion of time in crop decreased. Note, however, that the proportion of time in Stage I fallow decreased from 10% of the total system time in a 2-year system to 5% in a 4-year system with summer crops. Furthermore, the proportion of time in Stage III fallow, the worst water storage period, decreased from 19% to 11% for the same comparison.

Since precipitation storage efficiency in Stage I was only 10%–35% and was essentially 0% in Stage III, having a smaller proportion of the fallow time in these stages and more in Stage II, which is a highly efficient storage time, benefits the overall system. These shifts in fallow timing partially explain the advantage of the more intensive systems. An analysis of when precipitation is received relative to the fallow stages and the cropping season completes the explanation.

Farahani et al. (1998) demonstrated that during fallow Stages I and II one can expect to save 10%–35% and 50%–85% of the precipitation, respectively, which is in stark contrast to the 0% storage efficiency expected in Stage III. Data in Table 16.4 show that cropping intensification did not appreciably alter the proportion of the total agroecosystem precipitation received during fallow Stages I and II, which are the best water storage periods. However, intensification decreased the proportion of the precipitation occurring during fallow Stage III from 34% in a 2-year wheat–summer fallow system to 17% for a 4-year system such as wheat–maize–millet–fallow. Since no water can usually be stored in Stage III, this is a gain for the system. Furthermore, it dramatically increased the proportion of the precipitation received during the time when a summer crop could be grown.

TABLE 16.3
System Analysis: Time in Crop and Time in Various Fallow Stages for Three Cropping Systems in the Great Plains

System	Total Time in Crop	Total Time in Fallow	Time in Stage I	Time in Stage II	Time in Stage III
			Total Rotation Time (%)		
2-year (WF)	40	60	10	31	19
3-year (WMF)	39	61	7	42	12
4-year (WMPF)	38	62	5	46	11

Note: WF = wheat–fallow; WMF = wheat–maize–fallow; WMPF = wheat–maize–proso millet–fallow.

TABLE 16.4
System Analysis: Proportion of Precipitation Received in the Various Fallow Stages and during the Cropping Season for Three Cropping Systems

System	Precipitation in Stages I and II	Precipitation in Stage III	Precipitation in Cropping Season
	Total Precipitation for a Given System (%)		
2-year (WF)	34	34	32
3-year (WMF)	35	23	42
4-year (WMPF)	36	17	47

Note: WF = wheat–fallow; WMF = wheat–maize–fallow; WMPF = wheat–maize–proso millet–fallow.

In the Great Plains, this period of the year is especially favorable for summer crops such as maize, sorghum, sunflower, and millet.

Switching from a 2-year (wheat–summer fallow) to a 4-year system that includes summer crops such as maize or sorghum increased the proportion of the precipitation that fell while crops were present in the field from 32% in a 2-year system to 47% for a 4-year system. Receiving precipitation during the cropping period resulted in improved system PUE because the crop canopy and underlying residues left by the NT system absorb the raindrop impact, keep the soil surface cooler, which decreases evaporation, and the overall result is a net increase in soil water storage. Runoff also is diminished and the opportunity time for water infiltration is increased. An additional factor that contributes to improved water conservation during the cropping season is that the plants continuously exhaust the available water from the surface soil layers, which improves the infiltration rate because a dry surface soil is more receptive to water than a wet surface soil.

16.4.5 APPLICATION OF ANALYSIS TO OTHER CLIMATE SITUATIONS

Peterson and Westfall (2004) demonstrated that these principles of fallow stages can be applied to other agroecosystems. In the Great Plains situation analyzed by Farahani et al. (1998), most of the precipitation falls during the warmest time of the year, which is within the growing season for several well-adapted plant species. Analysis of a wheat–fallow agroecosystem in a Mediterranean climate in the eastern part of the U.S. state of Oregon, with an annual precipitation of approximately 400 mm like the Great Plains situation, revealed that the proportion of time in each fallow stage was the same as for wheat–summer fallow in the Great Plains because the fall planting and summer harvest dates of the winter wheat crop were essentially identical in both environments (Table 16.5). In a warmer Mediterranean climate near Settat, Morocco (annual precipitation approximately 400 mm), however, there were substantial differences in the proportion of time in each fallow stage and the time in crop. Wheat was planted later and harvested earlier in the Moroccan situation, which decreased the proportion of time in crop to 29% in contrast to 40% in the two cooler environments and increased the proportion of time in Stages I and III fallow. In the Great Plains environment, such a shift would have a negative effect on soil water storage because of the low precipitation storage efficiency possible in Stages I and III, but this was not the case in the warmer Moroccan environment as will be seen later.

Much larger contrasts appeared when the three environments were compared on the basis of precipitation distribution. In the Great Plains, only 32% of the precipitation fell while a wheat crop was in the field, which contrasted sharply with 46% for the Oregon environment and 50% for the Moroccan environment (Table 16.5). One of the major water savings in the Great Plains

TABLE 16.5
System Analysis: Proportion of Time in Fallow Stages and Proportion of Precipitation Received in a Wheat–Fallow System in Colorado and Oregon, U.S., and Morocco

Fallow and Precipitation Distributions	Climate	Stage I	Stage II	Stage III	Crop
			Rotation Time (%)		
Proportion of system[a] time in crop or fallow	Colorado	10	31	19	40
	Oregon	10	31	19	40
	Morocco	15	31	25	29
			Precipitation (%)		
Proportion of system[a] precipitation in each stage	Colorado	21	13	34	32
	Oregon	5	37	12	46
	Morocco	0	47	3	50

[a] System = 24 months for complete crop–fallow cycle.

environment was avoiding Stage III fallow because water storage efficiency was 0% in that stage. However, in Oregon, only 12% of the precipitation fell during Stage III, and in Morocco, only 3%, making avoidance of Stage III fallow much less critical in the two Mediterranean environments (Table 16.5). Furthermore, in Oregon and Morocco, 37% and 47% of the precipitation was received in Stage II fallow, respectively, and because of the cool temperatures, this was an excellent period in which to store water. In the Great Plains environment, which also has the potential for maximum storage in Stage II, there is much less precipitation to be saved. Note, however, that in the Oregon situation, extra attention to snow and snow melt retention would be required. In Morocco, there are no frozen soils and snow melt runoff problems, resulting in an even better period for soil water storage. Based on this analysis, it is plain that cropping intensification with warm-season plants such as maize or sorghum would have little chance for success in either the Oregon or Moroccan climate. Wheat and other cool season species obviously fit the Mediterranean environment very well relative to the Great Plains.

Peterson and Westfall (2004) suggested that scientists could use this approach to analyze precipitation and temperature distributions in relation to various crop species and thus identify the best intervention points for improved management. If fallow is used in a cropping system, one should make every attempt to avoid the periods when precipitation storage is likely to be grossly inefficient. The greatest PUE will be achieved if noncrop periods can be decreased in length and if crops are grown during the times when the precipitation is being received. The following are example applications of the analysis to climates with widely varying combinations of temperature and precipitation distributions.

16.4.5.1 Lanzhou, China (Lat. = 36°3′N; Long. = 103°47′E) (Annual precipitation = 328 mm)

The proportion of time in Stages I, II, and III and in crop production for this location, 13%, 33%, 16%, and 38%, respectively, were very similar to the Great Plains situation (Figure 16.6 and Table 16.6). The highest rainfall months coincide with the warmest temperatures and thus present an ideal growing season for warm-season plants. Although winter wheat is a common crop in the Lanzhou area, the precipitation and temperature distributions favor the production of summer crops such as

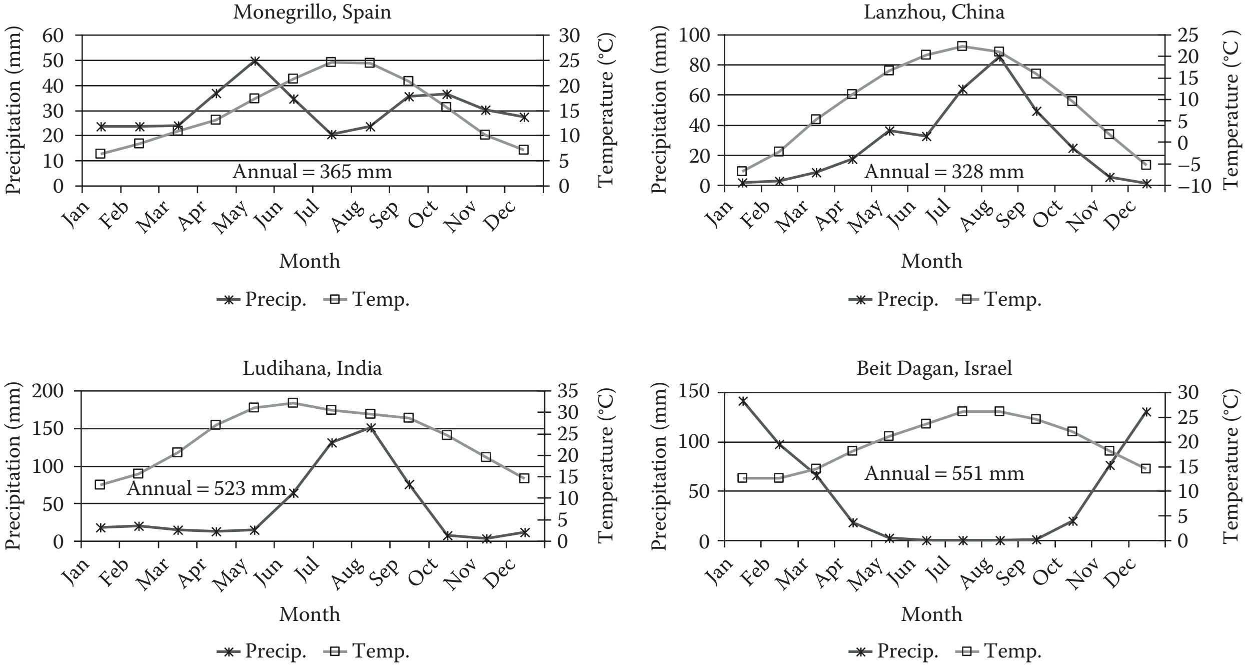

FIGURE 16.6 Long-term precipitation and temperature distributions for Lanzhou, China; Monegrillo, Spain; Ludhiana, India; and Beit Dagan, Israel.

TABLE 16.6
System Analysis: Proportion of Time in Fallow Stages and Proportion of Precipitation Received in a Wheat–Fallow System for the United States, Morocco, China, Spain, India, and Israel

Fallow and Precipitation Distributions	Climate	Stage I	Stage II	Stage III	Crop
			Rotation Time (%)		
Proportion of system[a] time in crop or fallow	Eastern Colorado	10	31	19	40
	Eastern Oregon	10	31	19	40
	Settat, Morocco	15	31	25	29
	Lanzhou, China	13	33	16	38
	Monegrillo, Spain	16	25	25	34
	Ludhiana, India	29	21	25	25
	Beit Dagan, Israel	16	25	25	34
			Precipitation (%)		
Proportion of system[a] precipitation in each stage	Eastern Colorado	21	13	34	32
	Eastern Oregon	5	37	12	46
	Settat, Morocco	0	47	3	50
	Lanzhou, China	30	15	35	20
	Monegrillo, Spain	16	23	27	34
	Ludhiana, India	44	7	42	7
	Beit Dagan, Israel	2	48	2	48

[a] System = 24 months for complete crop–fallow cycle.

maize, sorghum, sunflower, and millet, particularly if NT management is used. Interestingly, the August and September precipitation at Lanzhou tends to be greater than that of the Great Plains, which may permit the successful production of soybeans. Dryland soybean production has been unsuccessful in the west central Great Plains environment because of lack of adequate August precipitation.

Effective snow management will be necessary in this environment to maximize PUE since the winter precipitation is in the form of snow. Maintaining a standing residue cover during the winter months will provide good opportunity to capture snow and retain runoff, which can ideally be accomplished in an NT management system.

Based on this analysis, cropping intensification with warm season plants such as maize or sorghum should be good production possibilities in Lanzhou. Wheat and other cool-season species could be grown effectively in rotation with warm-season plants, and it is highly likely that no summer fallow is necessary at all.

16.4.5.2 Monegrillo, Spain (Lat. = 41°38′N; Long. = 00°25′W) (Annual precipitation = 365 mm)

The proportion of time in Stages I (16%) and III (25%) for this location are comparable to the Moroccan situation (Figure 16.6). The locations differ in that at Monegrillo, there is less time in Stage II (favorable water storage period) than in Morocco, but Monegrillo has more time in crop production. These conditions would seem to favor the production of cool-season crops such as wheat and barley at the Monegrillo site (Table 16.6). More significant, however, is that the precipitation distribution at Monegrillo differs from that of Morocco. During the fallow stages and the cropping period, the precipitation distribution is more similar to the Great Plains than to Morocco (Table 16.6). Monegrillo has less rainfall to store during the favorable storage in Stage II, more rainfall during the unfavorable storage in Stage III, and less rainfall during the crop period, compared to Morocco.

Based on this analysis, the Monegrillo environment is less favorable for cool-season crops such as barley and wheat than the Moroccan situation. Because summer temperatures are not as extreme and because there is some summer rainfall in Monegrillo relative to the Moroccan situation, summer crops such as sorghum and sunflower should be good possibilities for the Monegrillo site.

16.4.5.3 Ludhiana, India (Lat. = 30°54′N; Long. = 75°51′E) (Annual precipitation = 523 mm)

The distribution of fallow stages and crop production time at Ludhiana is more uniform relative to all other locations that have been compared to this point; Stage I = 29%, Stage II = 21%, Stage III = 25%, and the crop period = 25% (Figure 16.6 and Table 16.6). However, the precipitation distributions relative to the fallow stages and to the crop production period are totally nonuniform; Stage I = 44%, Stage II = 7%, Stage III = 42%, and the crop period = 7%. Since the summer temperatures in Ludhiana also are extremely high, the potential for soil water storage during either Stage I or III would be nearly zero. This situation, coupled with the small amount of the annual precipitation (7%) received during the favorable water storage Stage II, indicates that summer fallowing would be a very ineffective practice, even with the best NT practices. In this situation, production of adapted annual crops during the coolest times of the year would be the only feasible solution under nonirrigated conditions.

16.4.5.4 Beit Dagan, Israel (Lat. = 32°0′N; Long. = 34°49′E) (Annual precipitation = 551 mm)

The proportion of the crop rotation in the fallow stages and cropping period for Beit Dagan are identical to Monegrillo, Spain (Figure 16.6 and Table 16.6), which suggests that summer fallowing would be a marginal practice because over 40% of the time is either in Stage I or III fallow, which are the least favorable stages for soil water storage. However, the precipitation distribution pattern at Beit Dagan differs widely from that of Monegrillo, Spain; 48% of the precipitation at Beit Dagan occurs during the favorable soil water storage stage; and at Monegrillo, only 23% occurs during Stage II. Furthermore, at Beit Dagan, 48% of the precipitation occurs during the crop period, and at Monegrillo, only 34% occurs during this same period. Therefore, summer fallowing would be a better option at Beit Dagan than at Monegrillo. Both locations have high summer temperatures and thus favor the production of crops such as barley and wheat during the cooler periods of the year.

16.5 SUMMARY

Improving the PUE of dryland cropping systems in the semiarid regions of the world obviously is critical to adequate food production for many nations. We have found that adoption of NT management has permitted cropping system intensification in our environment, which has increased the system yield and profit. Furthermore, these new systems are very beneficial to the environment, since they decrease soil erosion by both wind and water. Understanding the constraints and opportunities that exist in a particular climatic situation is necessary to maximize the PUE. Our analysis uses precipitation, amount and distribution, and seasonal temperatures to estimate what type of cropping systems may be feasible.

In this chapter, we applied the analysis to four widely varying climate regimes. Each case was discussed, assuming the use of an NT management system, so as to maximize precipitation capture and retention in the soil. Each analysis resulted in a recommendation regarding the value of summer fallow and a recommendation regarding the production of either cool or warm season crops. To provide more specific recommendations, it would be necessary to know specific information about soils, crop markets, and infrastructure. It is our hope that the reader will perform similar analyses of their climate and production system and identify the potential ways for improvement.

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17 Historical and Present Usage of *Shatian* Gravel Mulch for Crop Production in Arid and Semiarid Regions of Northwestern China

Liang Wei-li, Gao Wang-sheng, Xu Qiang,
and Huang Gao-bao

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> Work the father to death, enrich the son, and impoverish the grandson.
>
> **—Lament of *Shatian***

17.1 INTRODUCTION

In some marginal areas, theoretically not suitable for crop production in terms of quantity of annual precipitation in northwestern China, farmers have survived for many generations and are trying to be better off by practicing a unique dryland farming system. The system involves growing crops on gravel-, pebble-, and/or sand-mulched land. Such a gravel-based cropland, along with the relevant farming system, is called *shatian* in Chinese.

While it is difficult to provide an exact terminological translation of *shatian*, it is easier to comprehend its significant effect on preserving rainwater in the soil. In a dry spring while soil moisture content in *shatian* is 13%–14%, sufficient for seed germination and seedling emergence, soil moisture content in the nonmulched field is about half (7%), which is not adequate for sowing a crop. Realizing the benefits of *shatian*, a satisfactory crop yield can be obtained even in an arid climate of 200–300 mm annual precipitation (Chen et al. 2008). This chapter specifically focuses on the description, origin, distribution, field operation, effects (on erosion, soil moisture, fertility, temperature, salinity, crop growth and development, yield, and quality), new advances, challenges, and research needs of *shatian*.

17.2 HISTORY AND DISTRIBUTION

17.2.1 ORIGIN OF *SHATIAN*

Shatian originated in Lanzhou of Gansu province of China, but there is no consensus on the exact year of its development and use. Some researchers claim that it was developed during the middle of the Ming dynasty dating back to 400–500 years ago (Li and Zhang 1982). By contrast, others believe that it was evolved during the Qing dynasty about 200–300 years ago (Xin 1993). Yet, some

BOX 17.1 AN OLD FARMER AND THE INVENTION OF *SHATIAN*

During the Kangxi period (~1662–1722 AD) of the Qing dynasty, there was a severe and perpetual drought prevailing in the Lanzhou region of Gansu province. Crops failed and people were suffering from extreme starvation. One day, an old farmer who lived in Qin-wang-chuan (the king of Qin's flat area) went to his farm to see the crops. Sad and depressed at the state of the crops, he walked away to answer nature's call. During this detour he came across a vigorously growing and healthy wheat (*Triticum aestivum*) plant. Surprised, he carefully examined the plant and its surroundings. The farmer observed that the wheat plant was growing at the opening of a burrow made by a rodent. Thus, the base of the plant was covered with gravel, pebbles, and sand. Upon removing the gravel and sand, the farmer noticed that the soil underneath was moist. Upon returning to the farm, the old farmer mulched his crop fields also with pebbles and gravel. His family became food-secure thereafter.

others argue that *shatian* was developed some 2000 years ago. Despite the controversy about the specific period of its origin, there is a general consensus regarding a popular story about the invention of *shatian* (see Box 17.1). It is thus hypothesized that *shatian* was invented much earlier but became popular only 200–300 years ago.

Farmers in Lanzhou are well experienced in crop production using *shatian*. They have developed special implements and field management techniques for this unique farming system for producing a wide range of crops (Figure 17.1). Spring wheat (*Triticum aestivum*), foxtail millet (*Setaria italica*), common millet (*Panicum miliaceum*), potato (*Solanum tuberosum*), and garlic (*Allium sativum*) are grown on rainfed *shatian*. By contrast, melons (*Cucumis dudaim*), vegetables, and fruits are grown in suburbs on irrigated *shatian*. Lanzhou owes its fame as the city of melons and fruits to the adoption of *shatian* (Huo et al. 2000). After the 1970s, cash crops have gradually replaced the food grains and are successfully grown on *shatian* (Yang et al. 2007).

17.2.2 CLASSIFICATION

Shatian is classified into different types depending on the type of mulch, with and without irrigation, age, and so on. Some commonly used *shatian* types are discussed below.

17.2.2.1 Composition of Mulching Material

Shatians are classified into two types depending on the nature of mulching material: *clear shatian* and *mixed shatian*. The clear *shatian* is mulched with gravel or pebbles, and little amount of soil is mixed in the gravel. Gravel or pebbles used for mulching are usually mined from the subsoil of nearby hills. The mixed *shatian* is mulched with gravel or pebbles with some soil mixed in. Mulching material for mixed *shatian* is obtained either from the hills or from a riverbed. In terms of crop yields, quality and agronomic productivity of mixed *shatian* are not as good as those of the clear *shatian*.

17.2.2.2 With or without Irrigation

Nonirrigated or rainfed *shatian* can have a life span of 40–60 years or even longer because there is no soil/silt brought in along with the irrigation water. *Irrigated shatian* plots are usually developed for growing cash crops, and are widely distributed in the vicinity of cities and towns. The mulch layer of irrigated *shatian* is relatively thinner than that of the rainfed *shatian*. Because silt and sediments are brought in with irrigation water, and frequent soil disturbance is needed for an intensive sequential cropping system, life span of irrigated *shatian* is usually 3–5 years—much shorter than that of rainfed *shatian*.

17.2.2.3 "Age" of *Shatian*

Depending on the age (duration since development), a *shatian* may be classified as new, mid-life, old, or duplex. The "age" is also indicative of the condition for its use for crop production.

New *shatian* are those developed within 15–20 years for rainfed *shatian* and 2 years for irrigated *shatian*. Mid-life *shatian* is developed within 20–30 years for rainfed *shatian* and in the 3rd year for irrigated *shatian*. Old *shatian* is developed beyond 30 years for rainfed *shatian* and after 4 years for irrigated *shatian*. Duplex *shatian* fields are those re-mulched with a new layer of gravel or pebbles on top of the previously mulched layer, to extend the life span of the *shatian* field for another 10–25 years after the previous one loses its functions.

17.2.2.4 Types of Mulching Materials

Different types of *shatian* are mulched with pebbles (round or semipolished gravel or *luan-shi shatian* in Chinese), flat gravel (flat rock fragment or *pian-shi shatian* in Chinese), and sands (*mian shatian* in Chinese. "*Mian*" means "soft" in Chinese). In the context of their effectiveness for water

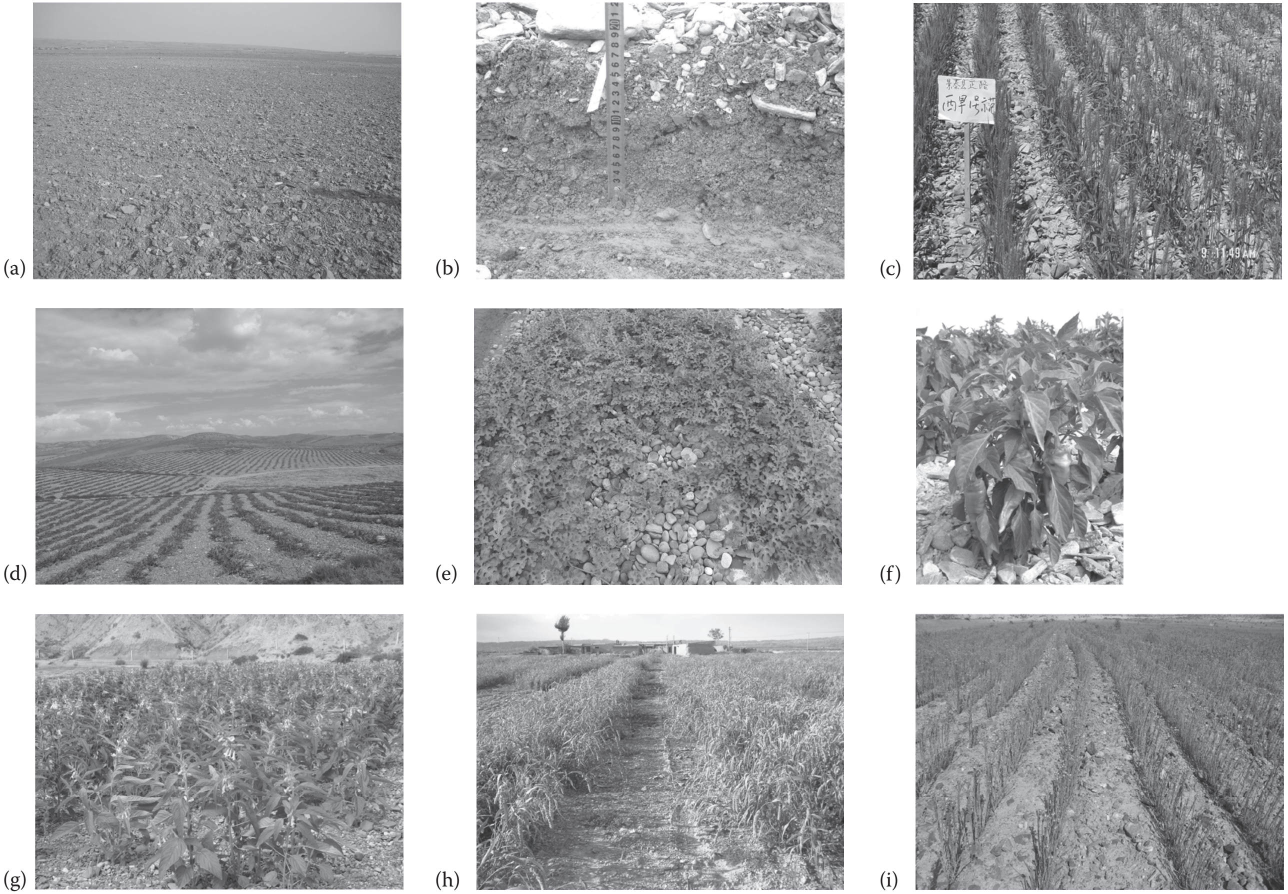

FIGURE 17.1 *Shatian* and crops: (a) gravel *shatian*; (b) a profile of the mulch layer of a gravel *shatian*; (c) spring wheat grown on *shatian*; (d) a *shatian* watermelon field; (e) pebble *shatian*; (f) chili pepper grown on *shatian*; (g) sesame grown on *shatian*; (h) millet grown on *shatian*; and (i) linseed grown on *shatian*.

conservation, sand *shatian* is not as good as that mulched with gravel or pebbles. Further, sand *shatian* has a much shorter life span than those mulched with gravel or pebbles.

This chapter focuses only on gravel- or pebble-mulched *shatian*.

17.2.3 Distribution of *Shatian*

> Dress in furs in the early morning, silk at noon, and sit aside a stove and eat watermelon.
>
> **—Local lyrics**

Major distribution areas of *shatian* are located in the Lanzhou district of Gansu Province, and in the counties of Zhongwei, Haiyuan, Xingren, and Zhongning of Ningxia Hui Autonomous Region, with a specific concentration in Gaolan and Baiyin Counties of Gansu and in the Xiangshan area of Zhongwei County of Ningxia (Figure 17.2). There are also scattered distributions of *shatian* in Xinjiang, Qinghai, Shaanxi, and Shanxi provinces or autonomous regions. The total area of *shatian* is estimated to be 0.17 million ha (Mha), of which 0.067 Mha is in Gansu and 0.068 Mha in Ningxia (Lu 2007; Xu et al. 2009a).

Principal soils in the major distribution areas of *shatian* are developed on the loess parent material, and are prone to erosion. *Shatian* fields are built on the summit and side slopes of hills with an elevation ranging between 1400 and 2500 meters above sea level (m.a.s.l). The climate in these areas is primarily arid or semiarid, characterized by inland continental and temperate monsoons, with cold dry winter, dry spring, and hot summer. With an annual precipitation of 180–400 mm, with a high variation between years and among seasons, more than 60% of it occurs between July and September. The mean annual pan evaporation of the region ranges between 1500 and 2200 mm (Yang et al. 2005).

Predominant ecological characteristics of the regions where *shatian* is practiced include dry, windy, stormy, highly variable precipitation, light soil, and large diurnal temperature variations. These characteristics are reflected in the lyrics "Dress in furs in the early morning, silk at noon, and sit aside a stove and eat watermelon." Box 17.2 gives two examples of the environmental feature of these areas.

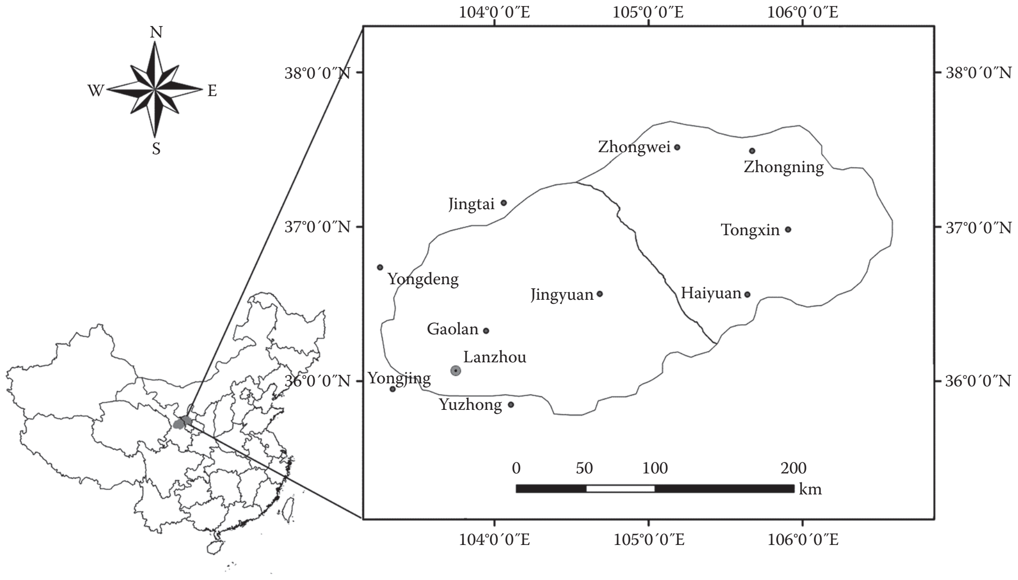

FIGURE 17.2 Major distribution area of gravel- or pebble-mulched *shatian*.

BOX 17.2 ENVIRONMENTAL FACTORS OF TWO TYPICAL *SHATIAN* DISTRIBUTION AREAS

Zhonghe, a township of Gaolan County, Lanzhou, Gansu Province, is located 1800 m.a.s.l. Soils are prone to erosion by water and wind. Soils contain 1.0%–1.1% organic matter (OM), 70–90 mg/kg total nitrogen (TN), 198–210 mg/kg total potassium (TP), 70–100 mg/kg available phosphorus (AP), and 120–160 mg/kg available potassium (AK), contained in the top 20 cm layer. The entire region is covered by sierozems. The soil bulk density of the 0–15 layer is 1.20 g/cm^3. The average annual precipitation is 263 mm and ranges between 154.9 and 392.4 mm. As much as 70% of the precipitation is received between June and September. The mean annual temperature is 7.1°C, the average temperature in the coldest month of January is −9.1°C and in the hottest month of July is 20.7°C. The accumulative thermal period above 0°C is 3324.5 degree days and above 10°C is 2798.3 degree days. There are 2768.1 h of sunshine. The average number of annual days of sandstorm is 2.6 with a maximum frequency of 9 (Yang 2004).

The Xiangshan area of Zhongwei County, Ningxia Hui Autonomous Region, is located on the extension of the Qilian Mountains. It has an elevation of 1500–2361 m.a.s.l. The original native vegetation in the area is arid desert steppe. The sierozem soils contain 0.3%–1.0% OM in the top 20-cm layer. The predominant *shatian* in this area is rainfed. The average annual temperature is 6.8°C. Accumulative thermal period above 0°C is 2332 degree days. Diurnal temperature variation ranges from 12°C to 16°C. With 2963.1 sunshine hours, the annual solar radiation load is 567.1 kJ/cm^2. Average annual precipitation is 247.4 mm, while the annual pan evaporation is 2172.3 mm. There are 146 frost-free days in a year. With strong wind and light soil, this region is among the major dust sources of Ningxia. Traditional crops of the region are millets, linseed (*Linum usitatissimum*), and wheat. The grain yield ranges between 1.5 and 2.0 tons per hectare for millets, between 1.8 and 2.3 tons per hectare for wheat, and between 2.23 and 2.7 tons per hectare for linseed. Crops fail completely in years of severe drought (Lu 2007; Xu et al. 2009b; Wang et al. 2010).

17.3 FIELD OPERATIONS

17.3.1 ESTABLISHING *SHATIAN*

Procedures of building *shatian* (Song 1994) include land selection, land preparation, basal application fertilizers, and application of mulch comprising laying of gravel or pebbles. Principal steps involved in establishing a *shatian* are the following:

Step 1: Land selection: Land with satisfactory soil fertility, flat or with a slope <15° is suitable for building *shatian*.

Step 2: Land preparation: Plow the chosen land once or twice, to the depth of 30–40 cm, level soil surface with a drag or a harrow, and then compact with a stone roller. In recent years, many *shatian* plots have been established without plowing the land before laying gravel or pebbles.

Step 3: Applying basal fertilizers: Broadcast fertilizers on the soil surface, and mix it in the soil by plowing or harrowing.

Step 4: Laying gravel or pebbles: This is preferably done during the winter when the soil is frozen and there are no other farm activities. The trafficability of heavily loaded vehicles is good on frozen soils, and the impact of vehicular traffic on soils is less. Further, labor is easily available during winter to uniformly apply the gravel and pebbles, which is an important criterion that must be met in establishing *shatian*.

Thickness of mulch: There are no formal standard criteria regarding the suitable thickness of mulch in building *shatian*. A wide range of thicknesses proposed include 10–15 cm (Song 1994), 5–10 cm (Yang et al. 1995), and 10–13 cm (Yang et al. 2005). Thickness of mulch is important because it determines the cost of building a *shatian* plot. The thickness also has a significant effect on the functionality of *shatian*. The commonly used thickness of mulch in Zhongwei of Ningxia is 7–15 cm. In general, a thin layer of mulch is suitable only for irrigated *shatian* because of the lesser dependence on conserving soil water (Lu 2007). A mulch layer thicker than 15 cm is good for conserving soil water, but it has three drawbacks: (i) increase in cost of establishing *shatian*, (ii) increase in labor hours for planting crops, and (iii) reduced penetration of rainfall water into soil beneath the mulch layer for rains of low amount. Lu (2007) recommended that the ideal thickness of mulch be 12–13 cm for rainfed *shatian*.

17.3.2 TILLAGE OF *SHATIAN*

Traditionally, the mulch layer of *shatian* is usually chiseled after the harvesting of the previous crop and before onset of rains. Chiseling is done by using the boot of an animal-drafted seed drill to enhance transport of the soil particles in the mulch to be washed down to the soil beneath. The repeated tillage operations are performed perpendicular to the previous tillage and to the same depth limited within the mulch layer. The field is harrowed just prior to the rainfall season (Yang et al. 1995). Two objectives of chiseling the mulch layer are (i) to remove soil particles in the mulch layer to the soil underneath and (ii) to break the crust in the mulch layer (Lu 2007). Nowadays, the tillage can be done with a tractor-drafted chisel plow (see Figure 17.3).

17.3.3 SOWING CROPS

High population density crops are sown with a seed drill while low population density crops (i.e., melons) are planted by hand. The procedure of planting watermelon is opening the mulch layer to shape a hole (see Figure 17.4) → soften the soil underneath with a hand shovel → open the soil 3–4 cm deep → put one or two germinated seeds into the opening → cover the seeds with soil → surround the hole with four gravel or pebbles of about 10 cm diameter → put another pebble on top to cover the seeded hole → uncover the hole after the seedling emerges. More than 60% of watermelons planted in *shatian* in the Zhongwei County of Ningxia follow this procedure (Lu 2007).

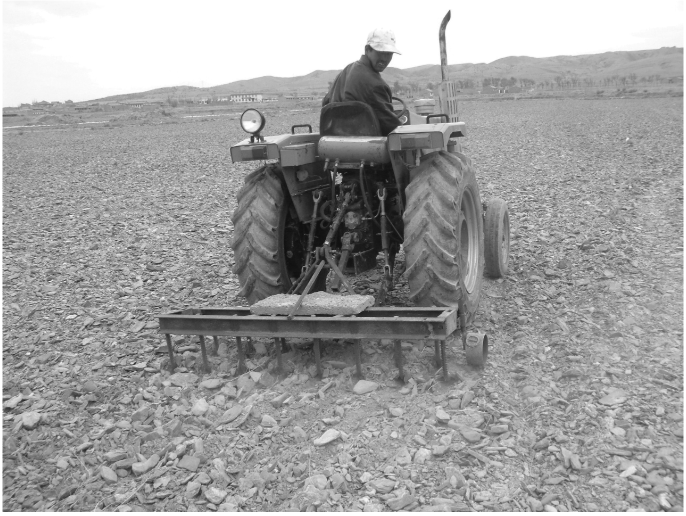

FIGURE 17.3 A farmer is tilling his *shatian* with self-made chisel-like implement.

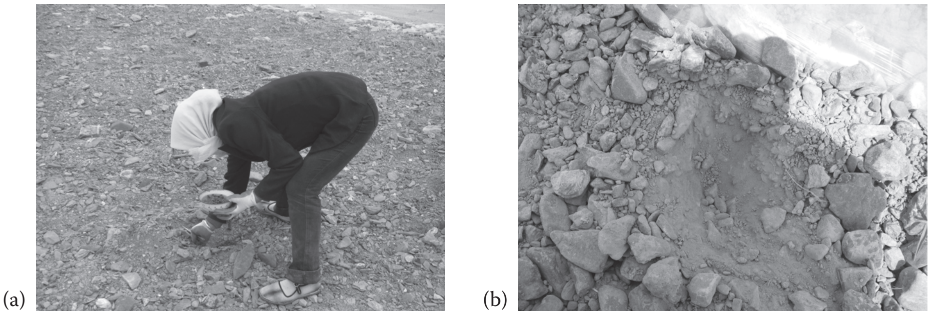

FIGURE 17.4 Planting watermelon on *shatian*: (a) making a hole and sowing by hand and (b) the sowing hole.

17.3.4 Applying Fertilizers on *Shatian*

The traditional approach of applying fertilizers on *shatian* is to remove the mulch layer in rows or open the mulch layer, soften the soil, apply fertilizers, and then level and compact the soil, and replace the mulch layer (Yang et al. 1995).

17.3.5 Restoration of Degraded *Shatian*

Shatian fields do not last forever, and have a fixed life span. A popular saying about *shatian* is "Work the father to death, enrich the son, and impoverish the grandson" vividly reflects the tremendous workload in establishing *shatian*, high productivity and profitability of new and mid-life *shatian*, and decline in productivity after the normal life span.

There are several factors influencing the life span of *shatian*. Important among these are the following:

1. Initial soil fertility: Since traditionally most rainfed *shatian* fields are not fertilized after establishment, the soil fertility and productivity decline with age. The difference in initial soil fertility could result in a difference in life span of *shatian* by 10–30 years.
2. Soil content in the mulch material used for establishing *shatian*: The lower the soil content in the mulching material, the longer is the life span.
3. Field management practices: All field management practices (i.e., tillage, fertilization, and sowing crops) should be implemented in a way that would minimally mix soil particles into the mulch layer. However, some mixing of soil particles into the mulch layer is unavoidable. Therefore, the function of *shatian* is weakened with cropping. *Shatian* loses its functions when soil particle content in the mulch layer exceeds 66% (Du 1993).
4. Sediment content in irrigation water: The reason that irrigated *shatian* has a shorter life span than the nonirrigated one is the silt content of the irrigation water. It is estimated that irrigation with water from the Yellow River brings 30 m^3 sediment per hectare into the field per year (0.3 cm/year).
5. "Dying out" of the underneath soil: The mellow top soil becomes less "active" because of a continuous cover as subsoil under the mulch layer for a long time without an adequate exposure to sunshine and air. A continuous gravel cover adversely impacts soil fertility and productivity of *shatian*.

A principal method of restoring a degraded *shatian* field is to remove the used mulch material, leave the land under fallow to restore fertility, or grow some low-nutrient demanding crops for 1 or 2 years, and then remulch the field with new material. In some cases, when the new mulching material is not easily available, the previous mulch material can be reused after sieving or washing off the soil particles in it. Because of higher soil particle content, which is equivalent to that of mid-life *shatian*, reusing the old material does not conserve soil water as well as using the new material (Wu and Feng 2006).

Field studies have shown that soil particle content in the mulch layer of *shatian* decreases within 1 year under fallow. Meanwhile, available soil nutrients and soil water storage are increased compared to the cropped *shatian*. Thus, it is possible to reclaim and sustain productivity of *shatian* by some means such as fallowing (Wu et al. 2008).

17.4 EFFECTS OF GRAVEL OR PEBBLE MULCHING

17.4.1 CONSERVING SOIL AND WATER

The most important effect of *shatian* is conserving soil water. The gravel or pebble mulch reduces water runoff, increases infiltration into soil, and decreases evaporation (E). The mulch protects the soil surface against wind and sunshine, disrupts capillary rise of soil moisture rising to the surface, and reduces soil E. These processes increase soil moisture storage in *shatian* (see Figure 17.5).

Yang (2004) summarized the data of past research and concluded that soil moisture content in *shatian* is significantly higher than in unmulched control. The data also showed higher moisture content in subsoil than in the surface layers. Therefore, rainwater in *shatian* infiltrates to a deeper soil depth than in a nonmulched field. This theme needs more systematic and in-depth study and analyses. Yang also concluded from the evidence of a higher increase in soil moisture in *shatian* than the increase in nonmulched field following a heavy rainfall (31.3 mm in 1 day) that *shatian* could accept more rainwater. While increase in infiltration of rainfall reduces runoff, the mulch also protects the soil against direct raindrop impact and significantly reduces soil and water erosion (Zhao et al. 2009). Li (2003) observed in a field experiment that among the 91 rainfall events, 18 produced a total runoff of 48.4 mm from the control plots, while only 6 produced 3.4 mm runoff from the *shatian* plots. *Shatian* significantly reduced runoff by increasing infiltration. Similar to reduction in water erosion, wind erosion in *shatian* is also significantly reduced (Wang et al. 2003; Xie et al. 2003). For example, Zheng (2004) observed that dust collected in *shatian* at 24 cm above the land surface was only 20% of that collected in a nonmulched field. The results of a research experiment in Zhongwei of Ningxia show that, compared to the nonmulched field, soil moisture in the top 20-cm layer during the period from April to June was 32.5% higher, average soil temperature in the 0–20 cm soil layer was 0.96°C higher, and the dust collected within 2 m height was 43.9%

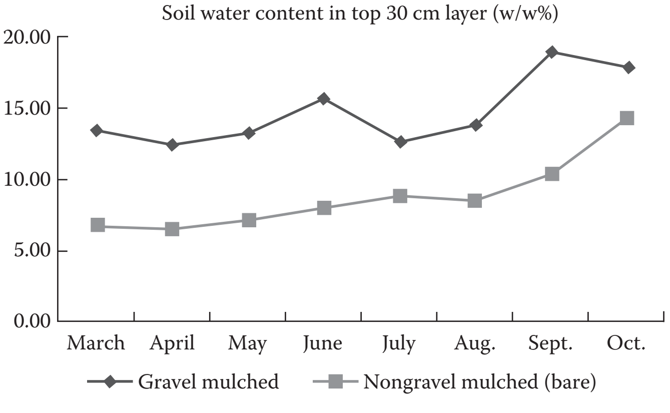

FIGURE 17.5 Comparison of soil moisture content in 0–30 cm layer in a *shatian* and nonmulched field. (Graph was drawn based on data calculated from the report of a gravel mulching survey team of Gansu Province, mimeographed unpublished document, 1964.)

less in *shatian* than in the unmulched field (Xu et al. 2009a). The result of a wind tunnel experiment (Li 2003) reveals that wind erosion of soil decreases constantly with the increase of pebble coverage at wind velocities of 10, 18, and 26 m/s, and the relation between wind erosion rate and pebble coverage rate follows a negative exponential function. Li's data from a field experiment (2003) implemented on *shatian* mulched with 10-cm-thick washed pebbles 5.0 cm in diameter at different surface coverages show a positive exponential correlation between surface pebble coverage and dust quantity trapped in *shatian* during the period from December 10, 2000 through May 10, 2001, the most windy period during a year.

Shatian not only conserves rainfall water in the soil during the growing season, it also preserves rainwater that falls during the postcropping season in the autumn and stores it in the soil for the crop grown in the following spring. Gao (1984) measured soil moisture content in *shatian* and nonmulched fields before and after the rainy season. The results showed that soil moisture content in *shatian* measured immediately after the rainfall season was approximately 20% higher, and that measured in the next spring before the rainy season began was 100% higher than that in the control. Research reports also show that during a year with severe drought, with a meager rainfall of hardly 10–15 mm, crops could not be sown in nonmulched fields but were successfully grown in a *shatian* field. Crops sown in *shatian* had a good stand, and yielded approximately 750 kg/ha compared with complete failure in the control (Song 1994; Yang 2004). Experimental data showed that soil water E in a period of 60 days in *shatian* was only 18.3% of that in a nonmulched field (Lü and Chen 1955).

Soil moisture content to 80-cm depth in *shatian* of different "ages" (ranging from 1 to 17 years) is higher than those in the adjacent nonmulched fields, although its effectiveness declines as *shatian* becomes "older" (Xu et al. 2009b). Soil moisture content in the 80 cm profile of *shatian* of 17 years age was 49.6% less than that under the newly established one, showing an average decline of 3.1% per year. After being cropped for more than 20 years and abandoned for 2 years, soil moisture content in the 80 cm profile of *shatian* was still significantly higher than that in the adjacent nonmulched field. Xu and colleagues also observed an interesting phenomenon that soil moisture content increased again in the subsoil layers of the profile after *shatian* was abandoned (fallowed) for 2 years. Wang et al. (2010) also reported that *shatian* of 1, 3, 5, 15, and 25 years of age stored 68.5%, 60.3%, 50.1%, 44.4%, and 40.4%, respectively, more soil moisture than a nonmulched field.

17.4.2 Increase in Soil and Air Temperatures

Gravel and pebbles have a lower heat capacity than soil, and thus warm up quicker under sunshine during the daytime than unmulched soil. Temperature of the soil beneath the mulch layer rises thereafter. At night, because of a higher moisture content and hence higher heat capacity, temperature of soil in *shatian* decreases slowly. Thus, soil temperature in *shatian* is higher than it is in nonmulched field during day and night. The difference in soil temperature between the two field types can be 1–2°C in spring and 3–4°C in summer (Gao 1984). Besides, because of a higher albedo and radiation reflection from gravel or pebbles, temperature of the near-ground air in *shatian* is higher than that in a nonmulched field. Lü and Chen (1955) reported that soil temperature in *shatian* was significantly higher than that in a nonmulched field in early spring and throughout the cropping season. The difference in soil temperature between the two field types was 1.5°C at night. Increase in soil temperature is most significant within the seedbed (0–8 cm soil depth). Diurnal variation in soil temperature in *shatian* is smaller than that in a nonmulched field. Lü and colleagues also observed that newly built *shatian* had a 2–3°C higher soil temperature than a nonmulched field and the date of soil being frozen was 20 days later and the date of thaw was 15 days earlier, which is extremely favorable to growing tropical crops (Lü and Chen 1955). Because of the favorable effects of *shatian* on soil moisture and temperature regimes, cotton has been successfully cultivated since the Jiaqing period (1796–1820 AD) of the Qing Dynasty in Lanzhou (Zhao 2009). Without *shatian*, the region is not favorable at all in terms of temperature and rainfall during growing cotton (Li and Zhang

1982). In Jingyuan County of Gansu Province, crops grown in *shatian* mature 10–20 days earlier than those grown in nonmulched fields (Song 1994). Research by Xu et al. (2009a) shows that soil temperature in *shatian* is significantly higher during the night and early in the morning, but is lower in 0–15 cm depth in the afternoon than in a nonmulched field. Li (2003) has also reported that soil temperature of *shatian* at 10 cm depth is 0.5°C–4.5°C higher based on hourly or daily measurements, air temperature at 20 cm height above the *shatian* surface is approximately 0.5°C higher than in the control, and daily variance of soil temperature is smaller in *shatian* than in the bare control. However, Li has observed consistently higher soil temperature in *shatian* during the day and night, which is different to Xu's observation. This is a topic of further in-depth and systematic study and analysis.

17.4.3 EFFECTS ON PLANT GROWTH, CROP YIELD, AND PRODUCE QUALITY

Wheat grown in *shatian* has a bigger root system, 20%–30% larger leaf area, and higher photosynthesis and transpiration (T) rates than in the unmulched control. Crops in *shatian* emerge and mature earlier. Spring wheat emerges 3–5 days earlier and matures 10 days earlier, tomato (*Lycopersicon esculentum*) matures 17 days earlier, Chinese cabbage (*Brassica rapa pekinensis*) matures 14 days earlier, and spring cabbage (*Brassica oleracea* L. var. *capitata* L.) matures 47 days earlier (Xie et al. 2003) than in the control field. In addition, the presence of the gravel or pebble mulch layer significantly reduces the incidence of insects, diseases, and weeds (Zhao et al. 2009).

In normal years, cereals grown in an unmulched field yield around 750 kg/ha and no more than 1125 kg/ha. By contrast, cereals grown in *shatian* can yield 1500–2250 kg/ha with a maximum of 3000 kg/ha. A crop grown in *shatian* seldom fails even in drought years (Song 1994). Since the adoption of *shatian* changes the microenvironment of the crop grown, it has turned large land areas with problems of inadequate water, low soil temperature, and/or high salinity into relatively highly productive and reliable arable lands, especially those lands in high-risk areas. Increase in yield of some crops grown in *shatian* can be as much as 50%–80% in cotton, 100%–300% in watermelon, and 40% in tropical vegetables (Yang 2004).

Crops grown on *shatian* not only yield more but also have better quality. Lanzhou's fame in high-quality products—wheat flour in the old brand of "He-shang-tou" (monk's head), honeydew (*Cucumis melo*), and rainfed watermelon—is entirely due to the contribution of *shatian* (Yang et al. 2004). Wheat on *shatian* has 10%–30% higher gluten and 21% higher protein contents than that in the control (Yang 2004). The sucrose content of honeydew grown on *shatian* is usually higher than 14%, and watermelon produced on *shatian* is much bigger in size, easier to transport, and can be preserved for a longer time period (can be consumed during the spring festival). Results from a field experiment show that yield, soluble carbohydrate content (SCC), and water-use efficiency (WUE) of watermelon are significantly higher for *shatian* than for the control treatments (Xie et al. 2006). Furthermore, since gravel and pebbles contain selenium, there is a higher selenium content of this health-beneficial microelement in *shatian* produce (Lu 2007).

Productivity of *shatian* declines with duration. Watermelons grown on *shatian* plots of 5–8, 10, 15, and 20 years of age yield 33.3%, 38.9%, 55.6%, and 71.1% less compared to those grown on 13-year-old *shatian* (Wang et al. 2010).

17.4.4 EFFECTS ON SOIL SALINITY

Greatly increased water infiltration into the soil and decreased evaporation from the soil in *shatian* reduce risks of soil salinity in the top layers. Data from field experiments show that soil salinity in the top 20 cm decreased sharply from 0.74 mg/g to 0.29 mg/g after 1 year of gravel mulching, continued to decrease slowly in the following 2 years, and was maintained at 19–22 mg/g in the succeeding years. Salinity in the top 20 cm soil in 25-year-old *shatian* increased slightly to 0.27 mg/g. Soil salinity had the same trend in 20–40 cm depth, with a slightly higher salt content (Wang et al. 2010). Xu et al. (2009b) reported a continuous and more significant salinity decline—0.21 mg/g in the first year and 0.05 mg/g in the seventeenth year after the *shatian*. Similar results have been reported by Li (2003) and Yang (2004).

17.4.5 Effect on Soil Fertility

Shatian under rainfed conditions is traditionally not fertilized. Xu et al. (2009b) compared rainfed nonfertilized watermelon *shatian* fields of 1–17 years in age with that abandoned for 2 years after more than 20 years of continuous cropping. Their results showed that after 17 years of continuous cropping, soil particle content in the mulched layer increased from 9.24% (the first year) to 36.15%; moisture content in 0–20 cm soil decreased from 25.3% to 13.7%; AP declined from 2.42 mg/kg to 2.26 mg/kg; AK declined from 172 mg/kg to 109 mg/kg; and OM, TN, and available nitrogen (AN) in the 0–20 cm soil layer increased in the first 4–5 years and declined continuously thereafter. The concentration of TN in 0–20 cm soil layer of the fifth year of *shatian* was 0.32 mg/g, 53.7% higher than in the 1st year of *shatian*; and AN in 0–20 cm soil layer of the 4th year of *shatian* was 15.1 mg/kg, which was 53.7% higher than that in the 1st year of *shatian*. While the AN concentration in the soil layer declined to 8.3 mg/kg in the 17th year of *shatian*, the soil OM content in the 17th year of *shatian* was 15.0% lower than that in the first year of *shatian*. Soil OM in *shatian* that was abandoned for 2 years after more than 20 years of cropping was 3.8% higher, AP was 2.4% higher, and AK was 31.2% higher than those in the 17-year *shatian*. These results support the conclusion that fallowing can restore soil fertility of *shatian* (Xu et al. 2009b).

Wang et al. (2010) reported a continuous decline of all soil nutrients in *shatian* being cropped from 1 to 25 years.

In recent years, even rainfed *shatian* fields are being fertilized, but soil nutrient dynamics under this new system have not yet been studied.

17.5 NEW DEVELOPMENTS IN PRODUCTION PRACTICES AND ADVANCES IN RESEARCH

New developments in production practices on *shatian* mainly consist of change in major crops, incorporation of plastic film with mulching, supplemental irrigation using harvested rainwater, intercropping and mechanization, and so on. Recent research efforts have been focused on high value crop production, mainly on watermelon and honeydew.

17.5.1 Change of Major Crops on *Shatian*

Risks of food insecurity prior to 1978 were the deciding factor, and *shatian* was mainly used for production of food grains. In recent years, however, *shatian* has been used for growing high-value cash crops, mainly watermelon and honeydew, although there are still small areas of spring wheat, Chinese date (jujube) (*Ziziphus zizyphus*), millets, potato, garlic, chili pepper (*Capsicum annuum*), soybean (*Glycine max*), and so on. Consequently, recent research efforts are aimed at change of the focus on increasing productivity, quality, and profitability of major cash crops (Yang 2004; Lu 2007).

17.5.2 Incorporation of Plastic Film

Plastic films have been incorporated in *shatian* in order to conserve and use the very precious water in a more efficient way and to further increase crop productivity and profitability. Plastic films are used in conjunction with supplemental irrigation using harvested rainwater. Several techniques have been developed for incorporating plastic in *shatian*, that is, single-film mulching, double-film mulching, triple-film mulching, and greenhousing (Wu and Zheng 1995; Yang et al. 2005, 2007). Patterns of the incorporation include *shatian* + ground plastic filming, *shatian* + plastic cloche, *shatian* + ground plastic filming + plastic cloche, and *shatian* + ground plastic filming + plastic cloche + plastic greenhouse (Ma et al. 2010). Recent studies have shown strong and positive effects of plastic film mulching in *shatian* in terms of quicker emergence and earlier maturity (Jia et al. 1998), preserving more soil moisture to ensure crop growth and development and yield improvements during the late phenological stages (Zhang and Zheng 2006; Xie et al. 2006). These positive effects are especially important during seasons of severe drought, and noticeable on seedling stand, early maturity, and yield (Yang et al. 2005). Early maturity is important to avoid early frost. By using plastic films, soil temperature at 10 cm depth can be increased by 4–6°C, soil moisture content in 0–5 cm layer by 15.23% in late April, and crop canopy receives more reflected radiation (Zhang and Zheng 2006; Lu 2007).

Many practical patterns of incorporation of plastic film have been developed by *shatian* farmers, which include the following:

- Covering the planting holes with plastic films: this is done by mulching the planting hole and its adjacent surrounding field surface, by making a mini plastic cloche above the hole, or by covering the hole with a transparent plastic bowl or cup (Jia et al. 1998; Lu 2007).
- Mulching the planted rows with plastic film on top of gravel or pebbles (Figure 17.6). Usually transparent films are used, but colored films are also used in places where aphids are a serious problem and black films are used where weeds are problematic (Yang 2004; Lu 2007). A *shatian* with plastic film mulch achieves a 52.5% higher watermelon yield than nonfilmed *shatian* (Jia et al. 1998). This is the most widely used pattern of *shatian* + film incorporation for its relatively lower cost, satisfying performance in conserving soil moisture, and ease of implementation by machines.

The effectiveness of different techniques of applying plastic film in terms of conserving soil moisture and increasing temperature are in the order of planting row mulching > planting hole mulching > planting hole covering by bow or cup (Zhang and Zheng 2006; Lu 2007). Different practices include the following:

- Cloche the planting row: immediately after crops (melons or any other cash crops) are seeded or transplanted, a transparent plastic film cloche is built over the planting row. The film is removed after flowering or fruit setting. With this technology, melons mature 25 days earlier than those on noncloched *shatian* (Yang 2004; Lu 2007).

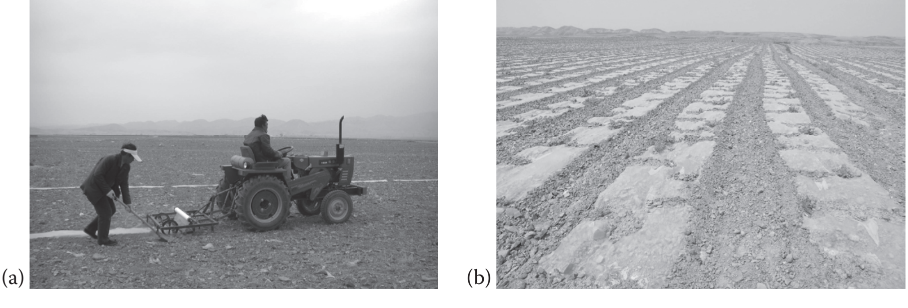

FIGURE 17.6 Incorporation of *shatian* with plastic film: (a) laying films and (b) young watermelon seedlings grown on *shatian* under film mulch.

Since the late 1990s, some more expensive and more complicated incorporation technologies have been developed (Yang 2004). Important among these are:

- Double use of plastic film: *Shatian* is mulched and then cloched with plastic film.
- Greenhousing: A plastic greenhouse built on *shatian* further shortens the growing period of crops. Watermelon and honeydew are grown on *shatian* in greenhouses equipped with modern ecological technologies of pest control, organic fertilizer application, and light-reflecting film to produce green food melons (Jia et al. 1998). Greenhouses built on *shatian* are widely seen in the Ping Chuan zone, Baiyin County of Lanzhou, Gansu Province.
- *Shatian* + ground plastic filming + plastic cloche + plastic greenhouse: The highest obtained yield of honeydew grown with this technology was 7.4 ton/ha in Shichuan township, Gaolan County of Lanzhou (Jia et al. 1998).

17.5.3 Mechanization

- A gravel/pebble *mulching machine* has been developed by Ningxia University (Figure 17.7a). The machine can mulch 0.33–0.47 ha with 10–15-cm-thick gravel/pebbles per hour.
- A mulch layer *softening and fertilization machine* has been developed by Jianfeng Machinery Factory of Zhongwei County (Figure 17.7b). The machine can also do weeding and sow wheat, buckwheat (*Fagopyrum esculentum*), sunflower (*Helianthus annuus*), and so on. It can loosen and fertilize 0.53–0.67 ha/hour, applying fertilizers up to the rate of 1200–2250 kg/ha.
- A planting–*hole-making machine* has also been developed by Jianfeng Machinery Factory. The machine can dig planting holes to a depth of 10–15 cm with an efficiency of 0.4–0.53 ha/hour.

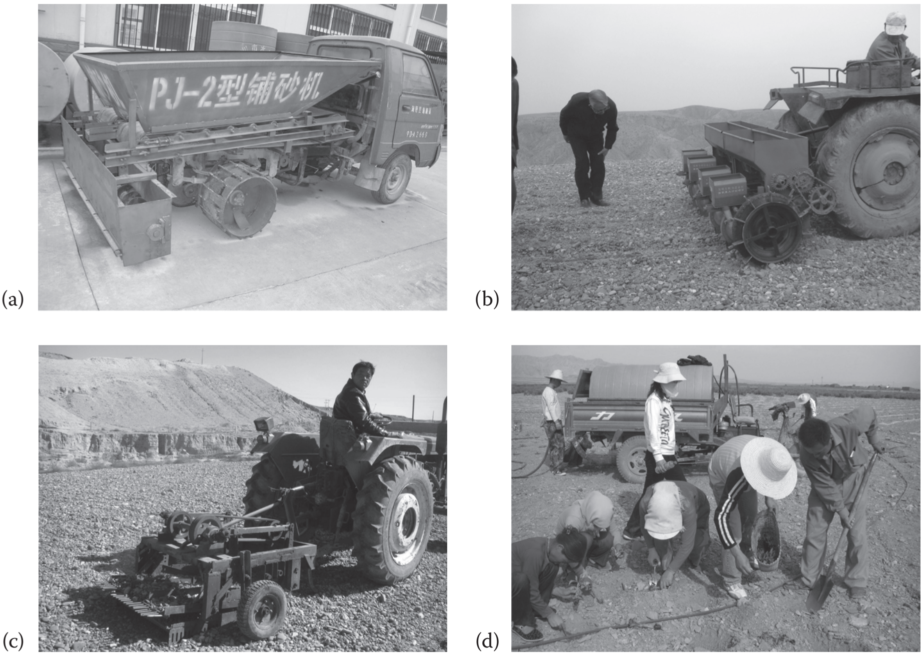

FIGURE 17.7 Machinery for *shatian* operations: (a) gravel/pebble-laying machine; (b) a *shatian* driller, which can also be used for softening the mulch layer, applying fertilizers, and sowing narrow row spacing crops (i.e., cereals); (c) gravel/pebble-sieving machine at work, and (d) farmers planting watermelon using water supplied by a water tank for supplemental irrigation.

- A prototype of a *gravel/pebble-sieving machine* (Figure 17.7c) to separate gravel/pebbles from sands/soil particles has been developed by Ningxia University and the Ningxia Association of Senior Scientific Workers.
- Several kinds of *supplemental irrigation machines* have been developed. Those machines can supply 1.6–6.4 m^3 water per hour (Figure 17.7d).

17.5.4 SUPPLEMENTAL IRRIGATION

In conditions of less rainfall, supplemental irrigation can greatly increase yield, profitability, and WUE of crop production on *shatian* (Zhang 1998; Wang et al. 2003; Tian et al. 2003). Supplemental irrigation by using the harvested rainwater at critical stages of crop growth increased watermelon yield by nearly three times (Tian et al. 2003). However, melons grown on rainfed *shatian* sell better than irrigated melons because of higher sucrose content and longer shelf life (can be preserved for consumption during the spring festival). Soluble solid content (SSC) is positively related to sucrose content, and thus is an easy-to-measure indicator of produce quality of watermelon. Research data show a close relation of SSC to soil water content which is significantly affected by rainfall, mulching, and supplemental irrigation. There are no significant differences in SSC among irrigated treatments below 68 mm under *shatian* conditions. However, SSC in the nonirrigated control is significantly higher than that with 68 mm irrigation (Wang et al. 2004). Applying irrigation water <45 mm has no significant effect on the sucrose content of watermelon, and that up to 67.5 mm can decrease the sucrose content by 4.4% or more (Wang et al. 2003; Xie et al. 2003). Thus, attention must be paid to the trade-offs between quality and yield.

17.5.5 INTERCROPPING OF MELONS WITH OTHER CROPS ON *SHATIAN*

Melons can be intercropped with peanut (*Arachis hypogaea*) (Wu and Lin 1999), chili pepper, Chinese date, soybean, sesame, and so on. Intercropping increases land productivity, increases profitability, and decreases the rate of degradation of *shatian*. Intercropping of melons with perennial crops (i.e., jujube) has the potential of using an aging *shatian* and restoring it (Wang and Zhang 2006; Lu 2007).

17.5.6 RESEARCH ADVANCES IN SUPPLEMENTAL IRRIGATION ON *SHATIAN* INCORPORATED WITH FILM MULCHING

Major recent advances in *shatian* technology include supplemental irrigation and its incorporation with plastic films. Xu et al. (2009b) studied soil moisture dynamics for a 0–80 cm profile with three mulching practices and a nonmulched watermelon field under rainfed and supplemental irrigated conditions. The results showed that average moisture content in the 0–80 cm soil profile for the entire growing season of all three mulched fields was much higher than that in the nonmulched field. Soil moisture content in the 0–80 cm profile in the fields mulched with both gravel and plastic film, with gravel only, and with films only was 44.2%, 34.0%, and 23.2% higher than those in the nonmulched field, respectively, under supplemental irrigation; and 71.9%, 73.7%, and 21.2% higher, respectively, under rainfed conditions (see Table 17.1). The effectiveness of mulching in conserving soil moisture is more significant under rainfed conditions. The small amount of supplemental irrigation (three applications of 22.5 mm total by watering only the planting hole) significantly increased the crop yield (Table 17.2).

Without considering the labor involved, profitability of the four treatments would be in the order of gravel + plastic film > gravel > plastic film > nonmulched under supplemental irrigated condition and gravel + plastic film > gravel > nonmulched > plastic film in rainfed conditions. Plastic film mulching made a small profit under irrigated conditions but could not recover the cost under rainfed conditions.

TABLE 17.1
Comparison of Soil Water Content in 0–80 cm Profile of Different Mulching Treatments and Nonmulched Watermelon Field (w/w%)

	Irrigated				**Rainfed**			
	G + P	**G**	**P**	**N**	**G + P**	**G**	**P**	**N**
Young seedling	21.6A	18.5B	17.7C	16.2D	17.3Aa	16.6Ab	14.3Bc	13.3Bd
Stem elongation	19.4A	18.1B	17.1C	16.8D	17.6A	15.6B	12.2C	10.7D
Flowering	19.5A	17.5B	16.6C	15.3D	18.1A	15.6B	12.1C	9.3D
Fruit setting	18.7Aa	16.7Bb	16.8Bb	12.3Cc	15.7A	17.0B	11.2C	8.7D
Fruit enlarging	17.1A	15.1B	14.2C	10.3D	14.6A	17.0B	10.2C	8.4D
Harvesting	18.4A	20.6B	15.5C	8.5D	16.5A	18.9B	10.1C	7.6D

Source: Xu, Q. et al. A study on soil moisture dynamics in dryland under different mulch materials. Unsubmitted/unpublished paper 2010.

Note: The experiment is randomized block designed.

G + P = gravel + plastic film mulched; G = gravel mulched; P = plastic film mulched; N = nonmulched.

Different letters in uppercase indicate statistically significant difference of 99% probability; different letters in lowercase indicate statistically significant difference of 95% probability.

Differences between irrigated and rainfed treatments at all growing stages are statistically significant at 99% probability.

Evaporation can be reduced significantly when the gravel surface in the watermelon field is mulched with plastic film (Xie et al. 2006). Obviously, gravel or pebble mulch is effective in increasing water infiltration into the soil but is not as good as the plastic film in reducing soil water evaporation. In comparison, a plastic film is effective in reducing soil water evaporation but also decreases the water infiltration into the soil. Therefore, plastic mulching has positive effects only under satisfactory soil moisture or irrigated conditions. In general, *shatian* is better adapted to the arid and semiarid regions than is the plastic film technology. However, a combination of the traditional and the new technology improves crop performance and increases the profit margin.

TABLE 17.2
Effects of Different Mulching Practices on Yield and WUE of Watermelon

	Irrigated				**Rainfed**			
	G + P	**G**	**P**	**N**	**G + P**	**G**	**P**	**N**
Yield (ton/ha)	24.80A	19.16B	7.41C	2.40D	20.38A	16.05B	4.21C	0.68D
Relative yield (%)	3628	2803	1084	351	2981	2349	616	100
ET (mm)	90.8a	91.0a	90.5a	91.1a	76.9A	81.1B	84.3C	87.8D
WUE (kg/ha/mm)	24.14A	18.65B	7.21C	2.33D	19.83A	15.62B	4.10C	0.67D

Source: Xu, Q. et al. A study on soil moisture dynamics in dryland under different mulch materials. Unsubmitted/unpublished paper 2010.

Note: The experiment is randomized block designed.

G + P = gravel + plastic film mulched; G = gravel mulched; P = plastic film mulched; N = nonmulched.

Different letters in uppercase indicate statistically significant difference of 99% probability; different letters in lowercase indicate statistically significant difference of 95% probability.

Differences between irrigated and rainfed treatments in ET and WUE are statistically significant at 99% probability, while yield difference between irrigated and rainfed treatments is statistically significant at 95% probability.

17.6 SOME CHALLENGES AND RESEARCH NEEDS

Major shortcomings of *shatian* include increased labor demand (extremely laborious), declining soil fertility, and mixing of soil particles with gravel or pebbles. Increasing efficiencies of *shatian* in high crop production for the entire life span of *shatian* and on a sustainable basis are among the principal objectives of future research.

- *Technical standards*: Thickness of gravel/pebble mulch and size of gravel/pebble affect cost of establishing *shatian* and the subsequent field operations. There is an ongoing debate on suitable size of gravel or pebble and gravel/sand or pebble/sand ratio to be used as the mulching material. Some researchers believe that the smaller the size, the worse the mulching material in conserving soil moisture because of lesser infiltration, stronger capillary function, and hence greater evaporation (Luo 1991). By contrast, others (Guan and Feng 2009) believe that a bigger size of mulching material conserves less soil moisture because of increased porosity and hence higher losses by evaporation. Lü et al. (1958) built *shatian* mulched only with gravel >5 mm in diameter (those <5 mm were removed by sieving). Results of a 3-year experiment showed that there was no difference in soil temperature between *shatian* mulched with pure gravel and that with mixture of gravel and sand; pure gravel mulch was more effective in conserving soil moisture; and yield of spring wheat grown on the pure gravel-mulched *shatian* (clear *shatian*) was higher than that grown on traditional *shatian* mulched with the mixture of gravel and sand. They concluded that this kind of *shatian* has a longer life span and is easier to perform mechanized operations on (Lü et al. 1958). Xie et al. (2006) reported that evaporation and E/ET ratio of *shatian* increased linearly with the increase in gravel size. Mulching with 2–5 mm diameter sand and gravel resulted in significantly less evapotranspiration (ET) than mulching with 5–20 mm and 20–60 mm diameter sand and gravel. They reported that gravel size had no significant effect on yield, but SCC of watermelon was significantly higher and WUE was significantly lower on *shatian* mulched with 20–60 mm diameter gravel than that on *shatian* mulched with 2–5 mm diameter gravel. They concluded that mulching with smaller-sized gravel improved WUE because of decrease of soil moisture evaporation, and the increased SCC with larger-sized gravel was because of an increase in diurnal soil temperature variance. These experiments indicate the need for further in-depth and systematic research on the suitable thickness of mulch, type and size of gravel/pebble, and their effects on soil moisture, temperature, and fertility.
- *Fertilization*: Difficulty in applying fertilizer has been one of the major shortcomings of *shatian* for a long time. Traditionally, fertilizers are not applied in most rainfed *shatian* fields, which results in decline of soil fertility over time. This problem must be addressed for the sustainable development of *shatian* (Chen et al. 2008). Fertilizer formulations and doses suitable for application on diverse crops and relevant easy-to-implement technology of fertilizer application in *shatian* must be given a high priority in future research (Tian et al. 2003; Wang et al. 2005).
- *Crop water demand in* shatian *and suitable areas for* shatian *development*: Under rainfed conditions, a minimum rainfall is needed for crop growth and yield. For example, watermelons grown on *shatian* need a minimum of 120 mm of rainfall during the growing season. In 2005, there was only 60 mm of annual precipitation in Zhongwei County of Ningxia, which resulted in a complete failure of melons in the county (Lu 2007). The water requirement of different crops is not known, especially the thresholds at different growth stages and in relation to soil moisture storage and rainfall patterns are not clearly understood. Yet, this is key important information for developing new *shatian*. In this context, long-term experiments are needed under different climatic conditions.

- *Crop rotation for disease control*: Since *shatian* is generally used for growing a limited number of crops, it is difficult to follow crop rotations. Lack of crop rotation results in the buildup of pathogens and soilborne diseases, which reduce crop yields. For example, watermelon is grown continuously without a crop rotation. Year after year of growing the same crop on the same piece of land can cause serious breakout of diseases with drastic yield losses (Liu and Zhou 2000). Research has shown that after 5–6 years of continuous cropping, watermelon should either be rotated with another crop or the land should lie fallow for 1–2 years (Luo 1991; Xu et al. 2009b). Currently, farmers either do not plant the melon in the same hole as was planted the previous year or grow low-yielding wheat. Long-term experiments on crop–soil–pathogen–disease dynamics are urgently needed for designing optimal crop rotation schedules.
- *Utilization of degraded shatian*: Degradation of *shatian* is inevitable, although its life span can vary greatly depending on the quality of mulching materials and field management practices. Restoration of degraded *shatian* to extend its useful life span is a possible alternative to building new *shatian*. Yet, little research has been done on this topic, except a limited research on the practice of intercropping watermelon with jujube in an old *shatian* field (Lu 2007).

17.7 SUMMARY

Research data and historical experiences indicate that *shatian* is indispensible because of its effectiveness in soil and water conservation. In the context of the present scenario in which economic status, market, means of production, public concerns for resources and environment, and so on have drastically changed, crop production on *shatian* has evolved into an entirely new farming system compared to the traditional system.

Some researchers argue that development of *shatian* should be restricted because it may result in unregulated mining of gravel and pebbles, which may damage the environment, destroy the vegetation, and degrade the land. However, it is not merely a question of the unregulated mining of gravel/pebbles. The principal issue is of a better administration and management (Yang 2004). There is also a concern that abandonment of the degraded *shatian* by the farmers would lead to the creation of an anthropogenic desert. Fortunately, there have been some practical solutions to address this concern. Important among these are new advances in *shatian* renewing technology and utilization of degraded *shatian*, and there are more and better solutions on the horizon. If people have the skills and innovations to build *shatian*, they must also be able to avoid the risks of creating an “artificial Gobi.”

Those who benefit from *shatian* are now expecting even more from it—to thrive by making full use of this miracle farming system. However, using *shatian* only for economic reasons would soon “degrade” it, as has been the case with the traditional *shatian*. Thus, sustainable use of *shatian* implies economic, ecological, and social aspects. Evolution of such a system requires in-depth scientific research.

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ABBREVIATIONS

AK	Available potassium
AN	Available nitrogen
AP	Available phosphorus
E	Evaporation
ET	Evapotranspiration
OM	Organic matter
SCC	Soluble carbohydrate content
SSC	Soluble solid content
T	Transpiration
TN	Total nitrogen
WUE	Water-use efficiency

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18 Improving Wheat Yield and Water-Use Efficiency under Semiarid Environment

U.S. Southern Great Plains and China's Loess Plateau

Qingwu Xue, Wenzhao Liu, and B.A. Stewart

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18.1 INTRODUCTION

Wheat (*Triticum aestivum* L.) is grown in a wide range of environments around the world and has the broadest adaptation of all cereal crop species (Briggle and Curtis 1987). Although the majority of wheat is produced in the range of 25–50° latitude, wheat production has expanded to the lower latitude (15°) as a cool season crop and to the higher latitude (60°N) as a warm season crop (Musick and Porter 1990). In addition, wheat is the number one food grain consumed directly by humans and provides more nourishment for people than any other food source. Wheat grains are the most important source of carbohydrates in the countries of temperate zone (Briggle and Curtis 1987). Therefore, wheat production plays a critical role in the world economy and food security.

Winter wheat is a major crop grown in the U.S. central and southern Great Plains (SGP). From 2008 to 2010, the wheat production from Colorado, Kansas, Oklahoma, and Texas was 27%–32% of the U.S. total production, ranging from 16.5 to 19.5 million tons (NASS 2010). In the U.S. SGP (the area includes the Texas High Plains, the Oklahoma Panhandle, parts of eastern New Mexico, southwestern Kansas, and southeastern Colorado), winter wheat is widely grown under dryland (rainfed), full-irrigation, and deficit-irrigation production systems and produced for both grain and winter cattle forage (Musick and Dusek 1980; Musick et al. 1994; Howell et al. 1995). The area has a semiarid climate with annual precipitation ranging from 380 mm in the southwest to 580 mm in the northeast and averaging about 480 mm. Growing season precipitation for wheat production averages about 250 mm (Musick et al. 1994). The seasonal evapotranspiration (ET) for winter wheat growth ranges from 700 to 950 mm when irrigation is used to prevent plants from water stress (Musick and Porter 1990; Musick et al. 1994; Howell et al. 1995, 2007). Therefore, the seasonal precipitation for winter wheat can only meet one-third of the ET required for maximum grain yield. As a result, wheat yield and water-use efficiency (WUE) are primarily limited by soil water deficits from late spring to early summer (Musick et al. 1994; Howell et al. 1997). Under dryland conditions, wheat production is largely determined by the amount and effective use of soil water storage and seasonal precipitation (Jones and Popham 1997). However, dryland wheat yields are generally much lower than irrigated wheat in the area (Musick et al. 1994).

In the U.S. SGP, irrigation application provides a means to maintain high yields and productivity in wheat. The irrigation water is mainly from the Ogallala Aquifer (Figure 18.1), and development of irrigation in this region significantly increased during the 1950s. The Ogallala is essentially a closed system with minimal recharge capacity, and the dramatic increase in water extraction for crop irrigation resulted in a significant decline in the water table; some areas have experienced up to 50% reduction in predevelopment saturated thickness. Irrigated land area has decreased from a peak of 2.4 million ha in 1974 to 1.9 million ha in 2000 (Colaizzi et al. 2008).

Similar to many other agricultural regions in the United States, the southern High Plains faces considerable challenges related to the domestic and global economy, climate change, and societal concerns over the impacts of agriculture on environments. Currently, several key issues hinder an adequate supply of wheat in the future. First, the growing world population continuously requires more production of food, forage, and fiber, particularly the major food crops such as wheat and corn (*Zea mays* L.). Second, in recent years, there is an increasing demand for

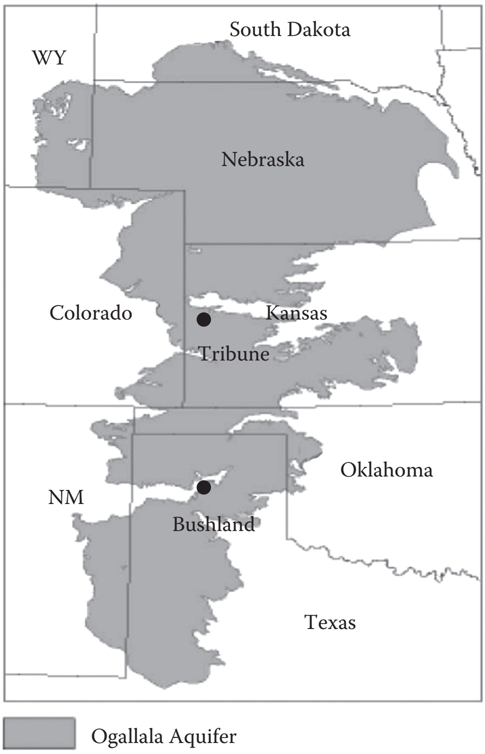

FIGURE 18.1 The map of Ogallala Aquifer in the U.S. Great Plains. The two locations (Bushland, Texas, and Tribune, Kansas) for long-term wheat experiments are shown on the map.

biofuel production in the United States, adding another pressure to current arable land areas. The increasing demands for energy independence and development of bioenergy crops in the United States mandate to consistently increase crop yields (Biomass Research and Development Board 2009). Third, the declining water table in the Ogallala Aquifer and increasing pumping costs will inevitably reduce irrigation (Musick et al. 1994; Stone and Schlegel 2006; Colaizzi et al. 2008). Fourth, the possibility for increasing frequency and severity of drought stress as well as other abiotic and biotic stresses under changing climate will likely reduce crop yields more frequently. The wheat yield and economic losses from the historic 2011 drought in Texas resulted in \$5.2 billion agricultural losses and the losses from wheat alone were \$243 million. The last two drought years in 2006 and 2009 resulted in \$4.1 and \$3.6 billion economic losses in Texas agriculture, respectively (Fannin 2011).

The Loess Plateau (LSP) of China is located in the middle reaches of the Yellow River, with a total area of over 600,000 km^2 and a population of 82 million (Figure 18.2). The region also has a semiarid climate with average annual precipitation in the range of 300–600 mm (Kang et al. 2002; He et al. 2003; Fan et al. 2005a). Precipitation distribution is very uneven, with more than 60% of precipitation falling in three summer months (July, August, and September). Wheat is the major crop in the region, and winter wheat is grown mainly in the southern part and spring wheat in the northwestern part of the LSP (Wang et al. 2009). The majority of crops including wheat are grown under dryland, which accounts for 90% of the total cropland area (Fan et al. 2005a). In the southern part of the LSP, continuous wheat (CW) is the most common cropping system, in which wheat is generally harvested in June and planted in late September or early October after a short

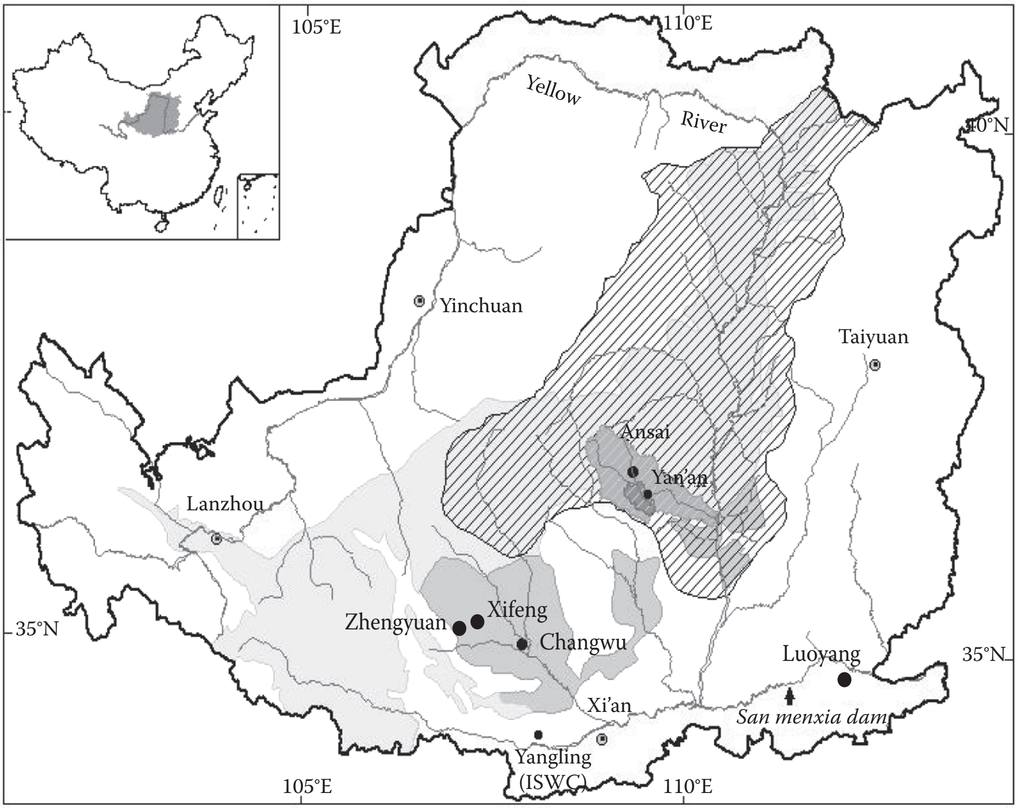

FIGURE 18.2 The map of China's Loess Plateau with an insert of the national map. The locations of long-term field experiment sites in winter wheat are shown on the map.

3 month fallow period. Wheat yields have increased significantly in the last 30 years in the LSP. For example, Huang et al. (2003) reported that average wheat yield has increased from 1.7 Mg/ha in the middle of the 1980s to 2.9 Mg/ha in the middle of the 1990s, as a result of increasing fertilizer applications. Recent reports showed that dryland winter wheat yields can be as high as 6 Mg/ha in research plots (Wang et al. 2011).

Like any other dryland farming area in the world, wheat production in the LSP is highly related to soil water storage and growing season precipitation for high yield (Li 1983; Huang et al. 2003; Liu et al. 2010). Therefore, drought stress is the most common factor limiting wheat yield. Although irrigation is possible in some areas along the rivers (Yellow River and its branches) or at surface water resources (e.g., dams and reservoirs), the available water resources in the region have been declining due to increasing water consumption for crop production and urban residential and industrial uses, hydraulic project constructions, and more frequent occurrences of drought (He et al. 2003). Therefore, the future wheat production in the LSP will likely depend on dryland production. Currently, the wheat production in the region also faces other challenges such as interests shifting from grain crops to cash crops (e.g., vegetables and produces), increasing nonfarming job opportunities, raising costs of fertilizers and farm machinery, environmental quality degradation, and possibly more unpredictable drought and heat stresses due to climate change (Fang et al. 2010).

Since water is the most important factor affecting crop production in the semiarid areas, the development of crop management practices to conserve water, optimize water use, and improve crop WUE becomes critical, particularly under a changing climate condition. Although increasing yield is an ultimate goal to any crop production system, maximizing WUE is of particular importance under water-limited conditions since lower WUE sometimes indicates a poor management and inefficient use of available soil water (ASW) (Musick et al. 1994; Passioura and Angus 2010). In this chapter, we review the research progress and identify the differences and similarities for improving wheat yield and WUE in the U.S. SGP and LSP of China. The development of

TABLE 18.1
Data Sets Used for Analysis of Yield, Evapotranspiration (ET), Water-Use Efficiency (WUE), Biomass and Harvest Index (HI), and Their Relationships in the U.S. Southern Great Plains and Loess Plateau of China

Region	Site	Location	Treatments	Years	References
U.S. Southern Great Plains	Bushland, Texas	35°11′ N 102° W	Irrigation and N rates	1981–1999	Eck (1988); Howell et al. (1995); Xu et al. (1998); Schneider and Howell (2001); Xue et al. (2006)
	Bushland, Texas	35°11′ N 102° W	Tillage and rotation	1984–1993	Jones and Popham (1997)
	Tribune, Kansas	38°28′ N 101° 45′W	Tillage and rotation	1973–2004	Stone and Schlegel (2006)
Loess Plateau of China	Changwu, Shaanxi	35°11′ N 107° 40′E	Fertilization and irrigation	1986–2009	Kang et al. (2002); Huang et al. (2004); Liu et al. (2007); Wang et al. (2011)
	Xifeng, Gansu	35°40′ N 107° 51′E	Crop rotation	1988–1991	Li et al. (2000, 2002)
	Zhengyuan, Gansu	35°30′ N 107° 28′E	Irrigation and mulching	1997–2003	Fan et al. (2005a)
	Luoyang, Henan	34°30′ N 113° E	Tillage and rotation	1999–2005	Su et al. (2007)

management strategies is the major focus, although breeding has played an important role for yield improvement. First, we examine the wheat yield—ET, WUE, and their relationships under a wide range of management practices. Then, we identify the current knowledge gaps and research priorities for improving yield and WUE to face future climate change and social economic challenges. In the entire chapter, we define WUE as a ratio of grain yield and seasonal ET, with a unit of kg/m^3. Another unit of WUE widely used in the literature is kg/ha/mm, which can be converted to kg/m^3 by multiplying by 0.1. The data sets for analysis in this chapter were mostly from long-term field experiments in both regions (Table 18.1).

18.2 YIELD DETERMINATIONS UNDER WATER-LIMITED CONDITIONS

For wheat, Passioura (1977) introduced a framework for identifying the important components for grain yield under water-limited conditions. Grain yield is determined by three components:

$$\text{Yield} = \text{ET} \times \text{WUE}_{\text{bm}} \times \text{HI}, \tag{18.1}$$

where ET is the seasonal evapotranspiration, WUE_{bm} is the water-use efficiency for biomass production, and HI is the harvest index, that is, the fraction of biomass partitioning to grains (Passioura 1977). Since these three components are likely to be largely independent of each other, an improvement in any one of them should result in an increase in yield as well as WUE. This framework has been proved to be very useful for identifying management strategies under water-limited conditions (Richards et al. 2002). Since the product of ET and WUE_{bm} is biomass at maturity (BM), Equation 18.1 can be rewritten as (Equation 18.2)

$$\text{Yield} = \text{BM} \times \text{HI}. \tag{18.2}$$

Improving biomass production, HI, or both will lead to higher yield under water-limited conditions (Blum 2009). In the SGP, Howell (1990b) showed that wheat improvement over the years was mainly contributed by increased biomass. The potential HI was relatively stable in the semidwarf cultivars. However, HI is generally low due to water stress during reproductive stages under semiarid environment (Schneider and Howell 2001; Xue et al. 2006).

18.2.1 YIELD, ET, AND WUE RELATIONSHIPS

In the U.S. SGP, the long-term dryland wheat yields ranged from 0 to 5 Mg/ha and seasonal ET ranged from 200 to 600 mm (Musick et al. 1994; Jones and Popham 1997; Xue et al. 2003, 2006; Stone and Schlegel 2006). In Bushland, Texas, the dryland yield was mostly 1–2 Mg/ha in long-term tillage and rotation studies (Jones and Popham 1997). However, dryland yields in irrigation studies were frequently over 3 Mg/ha (Musick et al. 1994; Xue et al. 2006). In Tribune, Kansas, the average dryland yield (3 Mg/ha) was generally higher than those in Bushland, Texas (1–2 Mg/ha) because Tribune is located north of Bushland where the evaporative demand is lower and the distribution of precipitation is more favorable during the reproduction period. Nevertheless, there were years with zero yields at both locations as a result of severe drought during the growing season (Musick et al. 1994; Stone and Schlegel 2006). The irrigated wheat yields ranged from 3.0 to 7.7 Mg/ha and ET from 400 to over 900 mm, depending on irrigation timing and frequency (Musick et al. 1994; Howell et al. 1995; Xue et al. 2003, 2006; Schneider and Howell 2001). Wheat yields under full irrigation were in the range of 5.3–7.7 Mg/ha and required about 700–950 mm ET (Howell et al. 1995; Schneider and Howell 2001; AgriPartners 2007). Under dryland conditions, WUE ranged from 0 to 0.8 kg/m^3, with an average of 0.4 kg/m^3. The WUE for irrigated wheat was higher than for dryland wheat and ranged from 0.5 to 1.2 kg/m^3 (Musick et al. 1994; Xue et al. 2006).

In the LSP of China, there exists a wide range of dryland wheat yields, ranging from 1.2 to 6.0 Mg/ha. The seasonal ET generally ranges from 200 to 500 mm. In the data collected in this paper, none of the data sets showed zero yields. The irrigated wheat yield in the region ranges from 3 to 7 Mg/ha but ET is mostly in the range of 300–500 mm, similar to the range of dryland wheat. Huang et al. (2004) showed a wider range of ET but the maximum ET was only about 650 mm. The wheat WUE in the LSP is generally higher than that in the U.S. SGP. For both dryland and irrigated wheat plots, WUE mostly ranges from 0.8 to 1.6 kg/m^3.

The wheat yield–ET relationship has been reported in different studies in the two regions (Musick et al. 1994; Schneider and Howell 2001; Kang et al. 2002; Huang et al. 2004; Stone and Schlegel 2006). Musick et al. (1994) summarized the yield–ET relationship based on long-term data in dryland and irrigated plots from 1958 to 1992 at Bushland, Texas. They showed a linear relationship between grain yield and seasonal ET pooling dryland and irrigated data together. The linear regression between yield and ET resulted in a slope of 1.22 kg grain yield per cubic meter of seasonal ET (kg/m^3) and a threshold of 206 mm ET (Musick et al. 1994). The threshold ET is defined as the minimum amount of ET required before any grain is produced (Musick et al. 1994; Kang et al. 2002). We analyzed the yield–ET relationship again by using the data from Table 18.1 and the results are shown in Figure 18.3. Similarly, there was a significant linear relationship between yield and ET, and the regression resulted in a slope of 1.06 kg/m^3 and a threshold of 175 mm ET ($Y = 0.0106X - 1.7393$, $R^2 = 0.75$, $P < 0.001$). The new data showed a slightly lower slope but a lower ET threshold as compared to those of Musick et al. (1994). Stone and Schlegel (2006) summarized dryland wheat data from 1974 to 2004 and showed a linear relationship between wheat yield and ET ($Y = 0.01X - 1.838$, $R^2 = 0.64$, $P < 0.0001$). The slope was 1.0 kg/m^3 and the ET threshold was 183 mm, which were close to the results from Bushland in Figure 18.3. The WUE based on the above linear regression analysis was about 1.0 kg/m^3 in the SGP region.

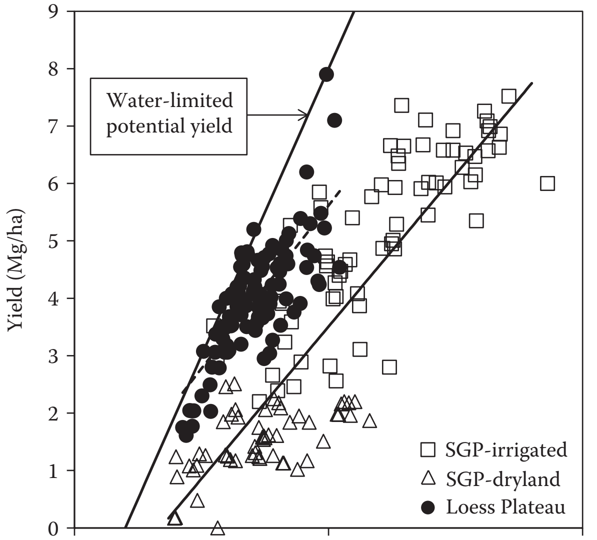

FIGURE 18.3 The linear relationship between yield and evapotranspiration (ET) in the U.S. southern Great Plains (SGP) (Bushland, Texas) and the Loess Plateau of China (LSP) based on the published data from experiments listed in Table 18.1. The lower solid line is the regression line for the SGP ($Y = 0.0106X - 1.7393$, $R^2 = 0.75$, $P < 0.001$), the dashed line is the regression line for the LSP ($Y = 0.0114X - 0.0645$, $R^2 = 0.60$, $P < 0.001$), and the upper solid line is the water-limited potential yield as a function of ET with a slope of 2.0 kg/m^3 and a threshold ET of 100 mm. The slope of 2.0 kg/m^3 represents an upper limit of WUE in wheat under water-limited conditions. (From Passioura, J.B. and Angus, J.F., *Adv. Agron.*, 106, 37–75, 2010.)

In the LSP, the yield–ET relationship was also a linear function ($Y = 0.0114X - 0.0645$, $R^2 = 0.60$, $P < 0.001$), pooling all data sets from Table 18.1. The linear regression of yield and ET in the LSP had a greater slope (1.14 kg/m^3) than that of the U.S. SGP (1.0 kg/m^3). Wheat yields are mostly higher in the LSP than in the SGP at any given ET level (Figure 18.3). Therefore, wheat in the LSP generally had higher WUE than in the U.S. SGP. The estimate of threshold ET for the LSP based on the linear regression in Figure 18.3 is unrealistically low (6 mm). The threshold ET may be estimated based on individual data sets. Kang et al. (2002) found a quadratic function between yield and ET and estimated the threshold ET of 152 mm. Huang et al. (2004), however, showed a linear regression equation between yield and ET ($Y = 0.0112X - 1.1358$, $R^2 = 0.66$, $P < 0.001$) and the threshold ET was 102 mm. Fan et al. (2005a) reported another linear relationship between yield and ET ($Y = 0.0115X - 0.696$, $R^2 = 0.55$, $P < 0.001$) and the estimated threshold ET was 61 mm. Obviously, the threshold ET for grain production was lower in LSP (61–152 mm) than in the U.S. SGP (175–206 mm).

The threshold ET is associated with the seasonal water loss through soil evaporation (Es). However, the threshold ET is not true Es and the accurate seasonal Es can be calculated in different methods (Howell 1990a). Estimate of Es based on linear regression of biomass and ET varied from 80 to 120 mm, with an average of 100 mm (Angus and van Herwaarden 2001). The Es generally counted 30% of total ET in some early studies in wheat (Angus et al. 1983; Howell 1990a). The threshold ET represented about 20% of maximum ET at Bushland, Texas, and still about 30% of maximum ET at Tribune, Kansas (Figure 18.3; Stone and Schlegel 2006). The threshold ET in the LSP was generally less than that in the SGP, and represented 12% and 16% of ET in the data sets from Fan et al. (2005a) and Huang et al. (2004), respectively. However, the threshold ET was 30% of ET based on Kang et al. (2002). It should be mentioned that threshold ET is lower in the areas with lowering seasonal ET (Musick et al. 1994). In the SGP, the maximum ET can be as high as 950 mm (Howell et al. 1995). However, the maximum ET in the LSP is generally less than 650 mm (Huang et al. 2004). The lower percentage of threshold ET (12%) from Fan et al. (2005a) was because of the use of plastic film mulching in their study, which can significantly reduce soil evaporation (Fan et al. 2005a).

The analysis of yield–ET relationship provides an important tool to identify wheat potential yield and yield gap between actual yield and attainable yield under water-limited conditions (Howell 1990a; Musick et al. 1994; Angus and van Herwaarden 2001). Angus and van Herwaarden (2001) set an upper limit of WUE in wheat under water-limited conditions based on the work of French and Schultz (1984). The upper solid line in Figure 18.3 is the water-limited potential yield as a function of ET with a slope of 2.0 kg/m^3 and a threshold ET of 100 mm. The slope of 2.0 kg/m^3 represents an upper limit of WUE in wheat under water-limited conditions (Angus and van Herwaarden 2001; Passioura and Angus 2010). In the LSP, there were some data showing that the wheat yield achieved to upper limit level. However, most of the yield data fall under the upper limit. In the case of the SGP, almost none of the data sets could reach the upper limit of yield potential. Figure 18.3 clearly showed that there is a large gap between potential and actual yields under water-limited conditions in both regions, and the gap was larger in the U.S. SGP. For each region, environmental conditions and management practices may both be responsible for the yield gaps. However, management practices can be more important to increase yield potential since environmental conditions are hard to control.

The relationship between wheat WUE and seasonal ET is shown in Figure 18.4. In the LSP, there was no clear relationship between WUE and ET. At any ET level (200–500 mm), WUE varied from as low as 0.7 kg/m^3 to as high as 1.5 kg/m^3. Although there was a positive relationship between WUE and ET in the SGP by pooling dryland and irrigated data together, the WUE also varied largely at the same ET level. The lack of significant relationship between WUE and ET indicated that WUE can be achieved under a wide range of ET. The variability in the amount and distribution of seasonal precipitation could be a major source of variation in ET and WUE (Musick et al. 1994). In the U.S. SGP, timing and frequency of limited irrigation might also contribute to part of

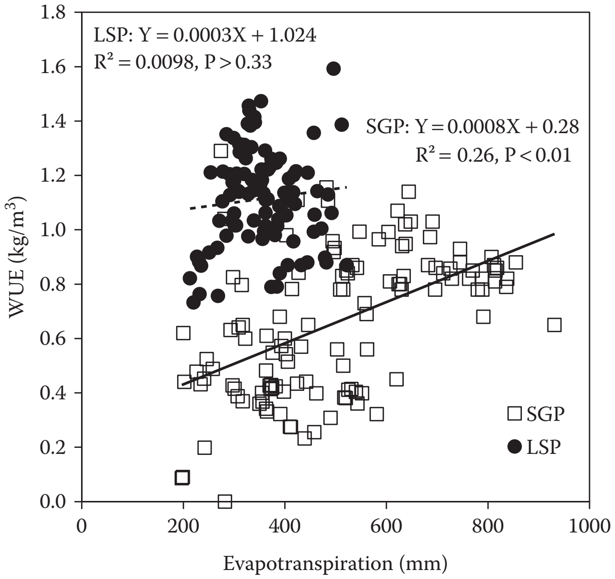

FIGURE 18.4 The linear relationship between water-use efficiency (WUE) and evapotranspiration (ET) in the U.S. southern Great Plains (SGP) (Bushland, Texas) and the Loess Plateau of China (LSP) based on the published data from experiments listed in Table 18.1.

the variation in WUE and ET. For example, at a similar ET level, irrigation between booting and anthesis stages could result in higher yield than irrigation from tillering to jointing (Musick et al. 1994). In the LSP, fertilization may significantly contribute to the variation in WUE given the same level of ET. Wang et al. (2011) showed that the average WUE in treatments fertilized with N, P, and manure was about 1.4 kg/m^3. However, WUE in treatments without fertilization or fertilized only with N averaged about 0.5 kg/m^3. All the treatments had about the same ET of 300 mm.

The relationship between WUE and yield is shown in Figure 18.5. In the LSP, WUE increased linearly as yield increased when pooling all the data from Table 18.1. In the region, a yield increase in 1 Mg/ha would lead to in an increase of 0.12 kg/m^3 in WUE. From individual data sets, Huang et al. (2004) showed a quadratic relationship between WUE and yield, and WUE did not increase further when yield was over 5 Mg/ha. In the U.S. SGP, the WUE–yield relationship was a quadratic function when the full range of yield was considered, which was similar to Huang et al. (2004). The WUE increased linearly when yield increased up to 4–5 Mg/ha. When yield increased further, WUE maximized and even tended to decrease. However, the initial slope between WUE and yield relationship was higher in the SGP than that in the LSP, with an increase of 0.28 kg/m^3 for every 1 Mg/ha of yield increase. Figure 18.5 indicated that higher WUE generally can be achieved with higher yields. However, a curvilinear relationship between WUE and yield showed that WUE might not be the highest when yield was in the high range. This is particularly true in the SGP. The ET demand could be as high as 12 mm/day and was frequently over 60 mm/week in irrigated wheat due to high winds and associated high vapor pressure deficit (Howell et al. 1995). As a result, it is difficult to achieve a very high WUE with full irrigated wheat in the SGP.

18.2.2 BIOMASS AND HARVEST INDEX

The relationship between aboveground biomass and ET in the SGP (based on Eck 1988; Schneider and Howell 2001; Xue et al. 2006) and the LSP (based on Kang et al. 2002) is shown in Figure 18.6a. In both regions, biomass increased linearly as ET increased. The linear regression of biomass and ET resulted in the same slope in the two regions (3.43 kg/m^3). However, biomass was always

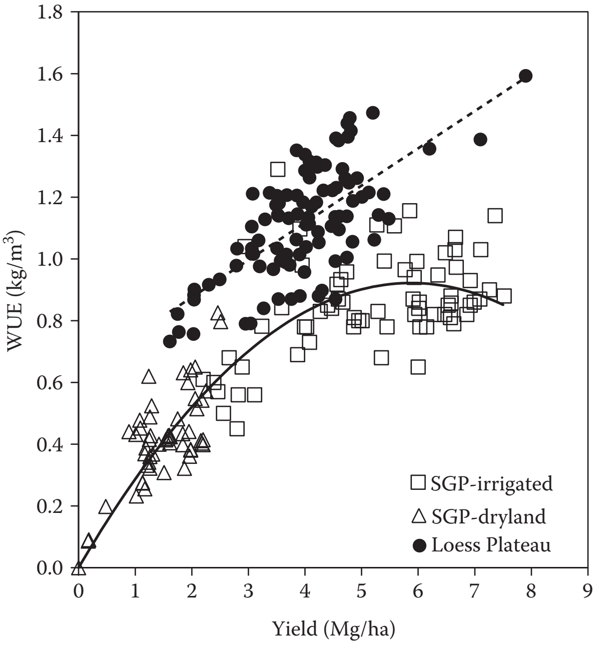

FIGURE 18.5 The relationship between water-use efficiency (WUE) and yield in the U.S. southern Great Plains (SGP) (Bushland, Texas) and the Loess Plateau of China (LSP) based on the published data from experiments listed in Table 18.1. (Regression equations: SGP: $Y = -0.0267X^2 + 0.3138X$, $R^2 = 0.785$, $P < 0.001$; LSP: $Y = 0.1206X + 0.6346$, $R^2 = 0.4746$, $P < 0.001$).

higher in the LSP than that in the SGP at a given ET level, indicating that wheat has a higher WUE_{bm} in the LSP environment (Figure 18.6a). However, the biomass difference at a given ET between two regions was much smaller than the yield difference (Figure 18.3). This suggests that the WUE_{bm} in the two regions is close but the WUE is very different. In the SGP, there was a wide range of biomass in different irrigation treatments (Eck 1988; Schneider and Howell 2001; Xue et al. 2006).

In both regions, grain yield is a linear function of biomass (Figure 18.6b). However, the slope of linear regression of yield and biomass was smaller in the SGP (0.23) than in the LSP (0.35), indicating that wheat in the LSP has higher HI than in the SGP. Kang et al. (2002) showed that the HI ranged from 0.25 to 0.45 in the LSP. Liu et al. (2007) reported a very high range of HI (0.41–0.62) in an irrigated study. In the SGP, Schneider and Howell (2001) showed a low HI range in irrigated wheat (0.21–0.32). Although Eck (1988) reported some high HI values (0.36–0.50), the HI is about 0.35 based on long-term wheat yield and biomass data (Howell 1990b). Nevertheless, increased WUE is largely contributed by increased HI under water-limited conditions as shown in Figure 18.7. The improved WUE as a result of higher HI was also reported in the Northern China Plain (Zhang et al. 1998) and Mediterranean environment (Oweis et al.2000).

18.3 MANAGEMENT PRACTICES FOR IMPROVING YIELD AND WUE

The above analysis of yield, ET, WUE, biomass, HI, and their relationships indicated that there were large variations in yield and WUE at different ET levels in both regions. As such, development of management practices is important to improve yield and WUE under water-limited conditions. Generally, there are two ways to improve crop performance: breeding and management practice. Improving wheat yield and WUE through breeding has been a major focus in semiarid environments (Richards et al. 2002, 2010; Reynolds et al. 2005). In the SGP, changes of grain yield under full irrigation over the years can reflect the genetic improvement of yield potential. In Bushland,

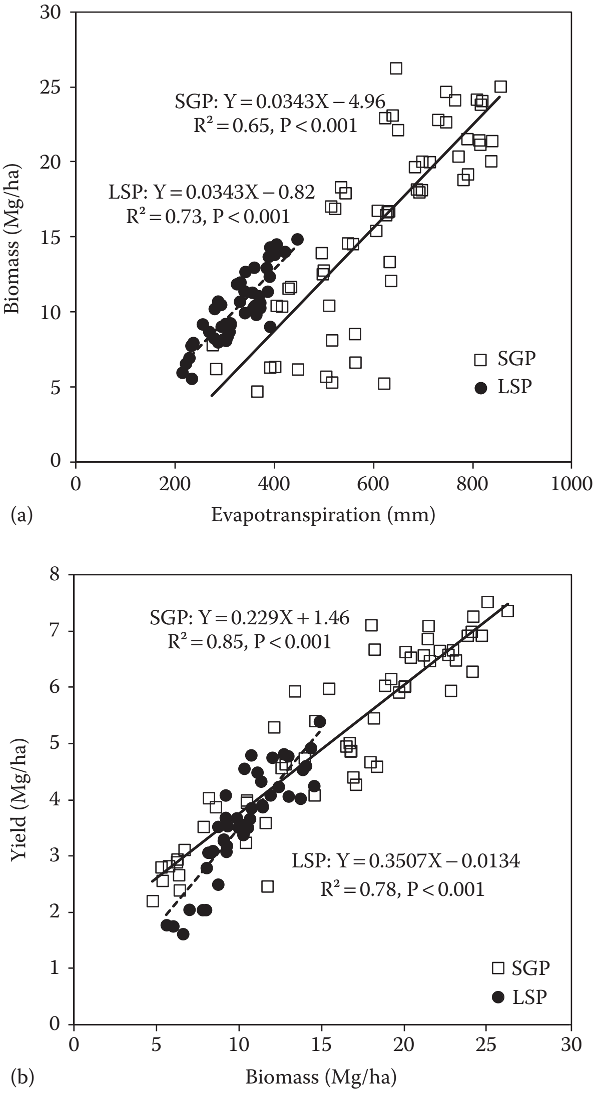

FIGURE 18.6 The relationship between (a) biomass and ET and (b) yield and biomass (SGP: Southern Great Plains; LSP: Loess Plateau). Data for SGP are from Eck, H.V., *Agron. J.*, 80, 902–908, 1988; Schneider, A.D. and Howell, T.A., *Trans. ASAE*, 44, 1617–1623, 2001; and Xue, Q., Zhu, Z., Musick, J.T., Stewart, B.A., and Dusek, D.A., *J. Plant Physiol.*, 163, 154–164, 2006. Data for LSP are from Kang, S., Zhang, L., Liang, Y., Hu, X., Cai, H., and Gu, B., *Agric. Water Manag.*, 55, 203–216, 2002.

Texas, the yield at full irrigation increased from 5.5 Mg/ha in the 1970s to 7.1 Mg/ha in the 1990s (Musick and Dusek 1980; Musick et al. 1994; Schneider and Howell 2001; Xue et al. 2006). The direct comparisons of cultivars released indifferent years showed that yield and WUE of new cultivars (released in the 2000s) increased over 20% as compared to those of an old cultivar (released in the 1970s) (Xue et al. 2010). Wheat yield increased significantly through breeding in China (Rudd 2009; Wang et al. 2009; Fang et al. 2010). In LSP, Zhang (1998) demonstrated that cultivars developed for irrigated conditions generally had higher WUE than dryland cultivars. In addition to yield improvement, WUE has also been increased through breeding. Zhang et al. (2010) demonstrated that wheat WUE increased from 1.0–1.2 kg/m^3 for cultivars from the early 1970s to 1.4–1.5 kg/m^3 for recently released cultivars in the Northern China Plain.

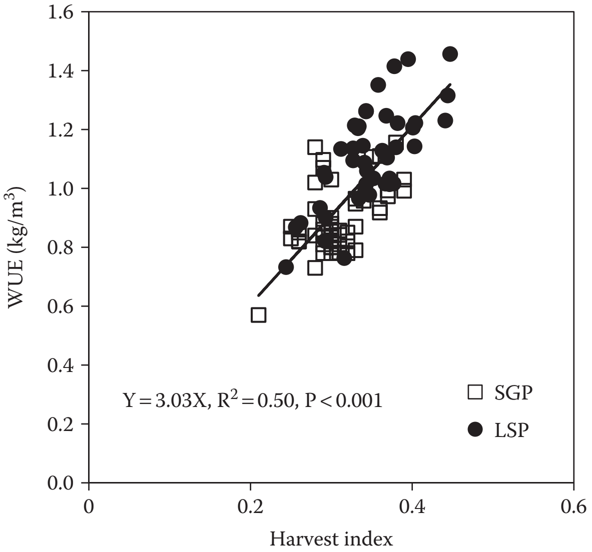

FIGURE 18.7 The relationship between water-use efficiency (WUE) and harvest index (HI). Data are from Xu, M., Xue, Q., and Musick, J.T., In *Ecophysiological Basis of Dryland Farming*, The Chinese Academic Press, Beijing (in Chinese), 1998; Kang, S., Zhang, L., Liang, Y., Hu, X., Cai, H., and Gu, B., *Agric. Water Manag.*, 55, 203–216, 2002; Schneider, A.D. and Howell, T.A., *Trans. ASAE*, 44, 1617–1623, 2001; and Xue, Q., Zhu, Z., Musick, J.T., Stewart, B.A., and Dusek, D.A., *J. Plant Physiol.*, 163, 154–164, 2006.

Management practices are as important as breeding to improve crop yield, water use, and WUE under water-limited conditions (Passioura and Angus 2010; Richards et al. 2010). Optimizing major management practices is important to maximize crop yields under water-limited conditions. Improved crop management is responsible for a large portion of increased productivity under water-limited conditions (Anderson 2010).

18.3.1 SOIL WATER CONSERVATION

Under semiarid environmental conditions, dryland wheat production is determined by both soil water storage and precipitation during the growing season since precipitation can meet only part of the seasonal ET requirement. Soil water storage at planting has long been a major focus in dryland wheat production (Musick et al. 1994; Stone and Schlegel 2006). In the SGP, Musick et al. (1994) analyzed the relationship between wheat yield and ASW at planting (1.8-m profile) based on 34 years of dryland wheat data in Bushland, Texas. There was a linear relationship between yield and ASW at planting ($Y = 0.0157X - 0.94$, $R^2 = 0.34$, $P < 0.001$). The linear regression resulted in a yield response of 1.57 kg/m^3 to soil water storage in a 1.8-m profile. In other words, increasing 1 mm of ASW at planting would lead to 15.7 kg/ha yield increase (Musick et al. 1994). Stone and Schlegel (2006) showed another linear relationship between ASW at emergence using 30-year dryland wheat data in Tribune, Kansas ($Y = 0.0098X + 0.828$, $R^2 = 0.32$, $P < 0.0001$) and resulted in a yield response of 0.98 kg/m^3 to soil water storage at emergence in a 1.8-m profile. In the LSP, soil water storage at planting generally accounted for 35.4% of the seasonal ET, but it can be as high as 52.6% in the years with low growing season precipitation (Li and Su 1991). Fan et al. (2005a) also found a linear relationship between wheat yield and ASW at planting in a 2-m profile based on a 7-year field study ($Y = 0.0172X + 2.422$, $R^2 = 0.38$, $P < 0.001$). The linear regression resulted in a slope of 1.72 kg/m^3. The linear relationships between yield and ASW at planting or emergence emphasize the importance of preseason soil water storage and conservation of precipitation for dryland wheat production in both regions. For the linear regressions from Musick et al. (1994) and

Fan et al. (2005a), the slope of the regression between yield and ASW at planting was much higher than that of the regression between yield and ET (1.57 vs. 1.22 kg/m^3 for the SGP, 1.72 vs. 1.15 kg/m^3 for the LSP). This suggests that ASW at planting is important for wheat plants to effectively use precipitation during the growing season (Fan et al. 2005a). The lower R^2 of regression between yield and ASW at planting or emergence (<0.40) indicated that wheat yield is affected by other factors. In the SGP, seasonal precipitation (from October to June) accounted for the majority of dryland wheat yield variation (55%) (Musick et al. 1994). Huang et al. (2004) showed that precipitation during the late growing season (May and June) was important for dryland yield in the LSP.

Soil water storage is determined by the amount of precipitation as well as the efficiency of precipitation storage during the fallow period. In the SGP, management practices for increasing soil water storage have been focused on crop rotation, tillage systems, and residue management (Musick et al. 1994; Jones and Popham 1997; Stone and Schlegel 2006; Stewart et al. 2010). Dryland wheat may be grown under different rotation systems such as CW, wheat–fallow (WF), and wheat–sorghum (*Sorghum bicolor* L.) – fallow (WSF). The tillage systems include conventional tillage (CT) and no-till (NT) with wheat residue mulch. Jones and Popham (1997) investigated the effects of rotation and tillage systems on dryland wheat and sorghum production and WUE in a 10-year study (1984–1993) at Bushland, Texas. Among the different rotation systems, ASW at planting was always lower in the CW system than in the WF and WSF systems. The 10-year average ASW amounts at planting were 156, 212, and 205 mm for CW, WF, and WSF, respectively. For the tillage systems, NT significantly increased ASW at planting (199 mm) as compared to stubble mulch (183 mm). The precipitation storage efficiency (PSE) was generally low in Bushland, Texas, for wheat. Among the various treatments, WSF generally had higher PSE (about 17%) than WF (11%) and CW under stubble mulch (14%). However, NT with wheat residue mulch in CW resulted in a higher PSE (20%) than WSF, indicating that NT is an important practice for improving PSE in the Great Plains environment (Jones and Popham 1997). The above-mentioned long-term study clearly demonstrates that the WSF system under NT provided significant benefits for improving wheat yield and WUE, as a result of increasing ASW at planting and PSE. On average, the annual grain production was 1.8 Mg/ha for WSF (wheat and sorghum) but only 1.0 Mg/ha for CW (wheat only) (Jones and Popham 1997). Norwood (1994) compared conventional and NT tillage under WF and WSF systems. Although they did not find differences in wheat WUE between CT and NT, less evaporation and runoff in the NT system promoted water moving to deeper soil profile in the WF and WSF systems. Stone and Schlegel (2006) sorted the wheat yield and WUE data by tillage and showed that NT significantly increased dryland wheat yield and WUE. The wheat yield response to ET was greater with NT (1.38 kg/m^3) than with CT (0.86 kg/m^3). Stone and Schlegel (2006) also summarized the additional water increase in the soil profile during the fallow period as a result of NT, compared with CT in the Great Plains. The soil water increase due to NT ranged from 15 mm in the SGP to 87 mm in the central Great Plains, depending on rotation systems.

In the LSP, winter wheat is predominately grown under the CW system under CT. The fallow period is only for 3 months (July–September). Since most of the precipitation (>60%) falls during the wheat fallow period, improving PSE becomes critical for enhancing ASW at planting (Shangguan et al. 2002; Jin et al. 2007; Wang et al. 2011). Shangguan et al. (2002) showed that the PSE in the LSP was about 35%–40%. Jin et al. (2007) and Wang et al. (2011) showed a wide range of PSE (12%–43%), depending on year, tillage system, and fertilization. The conventional deep tillage has long been used to improve PSE (Fang et al. 2010). For example, Wang et al. (2002) showed that about 90% precipitation can be stored in soil by deep tillage. However, deep tillage may affect soil properties without residue mulching (Fang et al. 2010). Jin et al. (2007) investigated the effect of five tillage systems on dryland wheat yield, PSE, and precipitation use efficiency (PUE) in a 5 year field study (2001–2005). The tillage systems included CT, subsoiling with mulch (SS), NT with mulch (NT), reduced tillage (RT), and two crops per year (TC, winter wheat and peanut). Among the tillage systems, SS resulted in highest PSE, PUE, and crop yield. Although the NT system was slightly less effective than SS, NT had a significant effect on water conservation and increased PSE by 12%

as compared to CT (Jin et al. 2007). In contrast to the SGP, the NT practice is generally not popular in the LSP. However, the NT may provide a long-term benefit and continuous NT practice would result in a higher yield in the long run (Jin et al. 2007).

Crop residue mulch can provide an effective way to increase PSE and WUE. Jin et al. (2007) found that the highest PSE (41.6%) was obtained under NT with wheat straw mulch. Deng et al. (2006) indicated that using crop residue mulching can reduce soil evaporation by 36% in winter wheat. Wheat straw mulching can be easily implemented and has been increasingly adopted by producers in the LSP (Deng et al. 2006). Plastic film mulching is another technique to conserve soil water. Fan et al. (2005a) reported PSE, yield, and WUE in a 7-year field study using plastic film mulching. They showed that plastic film mulching resulted in a very high PSE (70%) as compared to without plastic film mulching (35%). Meanwhile, the ASW at planting (2-m profile) increased from 62 to 123 mm as a result of plastic film mulching. However, plastic film mulching is not widely used in field crops. Instead, it is applied more often in some high-value cash crops such as vegetable and oil crops. In addition, plastic film mulching may cause environmental problems such as difficulty of removal and disposal (Gao et al. 2009; Fang et al. 2010). Fertilization is an important practice to increase PSE in the LSP. Wang et al. (2011) reported PSE, yield, and WUE in a long-term fertilization study. They found that wheat plots fertilized with N (120 kgN/ha) and P (60 kgP_2O_5/ha) significantly increased PSE from 28% to 34% as compared to those without fertilization. As a result, fertilization significantly increased wheat yield and WUE (Wang et al. 2011).

18.3.2 SEEDING FACTORS

Management practices related to seeding and wheat stand establishment include seeding date, rate, depth, row spacing, and quality (seed size, protein content, etc.). Among the seeding factors, seeding date and rate have long been studied since they are easily controlled by producers in most cropping systems (Paulsen 1987). Selection of optimum seeding date and rate can be important for wheat yield and WUE (Musick and Porter 1990; Chen et al. 1991; Winter and Musick 1993; Shangguan 1998). In the U.S. SGP, there is a wide range of seeding date for winter wheat (August–November). The wide range in seeding date in the region is because of dryland and irrigated cropping systems either with or without grazing, and highly variable weather conditions. For grain production, early October is normally considered as optimum seeding date. However, the seeding date may be delayed to November due to dry weather conditions (Winter and Musick 1993). Musick and Dusek (1980) investigated the seeding date and irrigation effects on wheat phenological development and yield. In general, early (September 15) and normal (October 12) seeding dates resulted in a higher yield than a later seeding date (November 7). Early to normal seeding significantly increased biomass production as compared to late seeding. Seeding date affected soil water use and root growth pattern. Winter and Musick (1993) showed that wheat plants seeded in August had low grain yield since the plants used most of the soil water in the fall and experienced severe water stress in the spring. Wheat seeded in October used as much soil water as August seeding by anthesis and produced high grain yield. By contrast, wheat seeded in November had a very shallow root system, did not use much soil water, and produced low grain yield (Figure 18.8). In the U.S. Great Plains, the most widely recommended seeding rate for wheat is 67 kg/ha or 200 seeds/m^2 (Paulsen 1987). However, seeding rate varied with cropping systems (dryland or irrigated) and seeding date (early or late) (Paulsen 1987; Musick and Porter 1990; Musick et al. 1994). Seeding rate ranged from 60 to 100 kg/ha (176–300 seeds/m^2) in irrigated wheat and from 35 to 50 kg/ha (100–150 seeds/m^2) in dryland wheat (Musick and Porter 1990; Musick et al. 1994). Seeding date and rate can interact to affect wheat grain yield (Dahlke et al. 1993; Spink et al. 2000). Higher seeding rate is normally required if the seeding date is delayed from optimum date because any delay in seeding normally reduces plant growth and tiller production (Dahlke et al. 1993; Spink et al. 2000). In general, the seeding rate should be increased by 10% per week of delay in seeding after the optimum seeding date (Paulsen 1987).

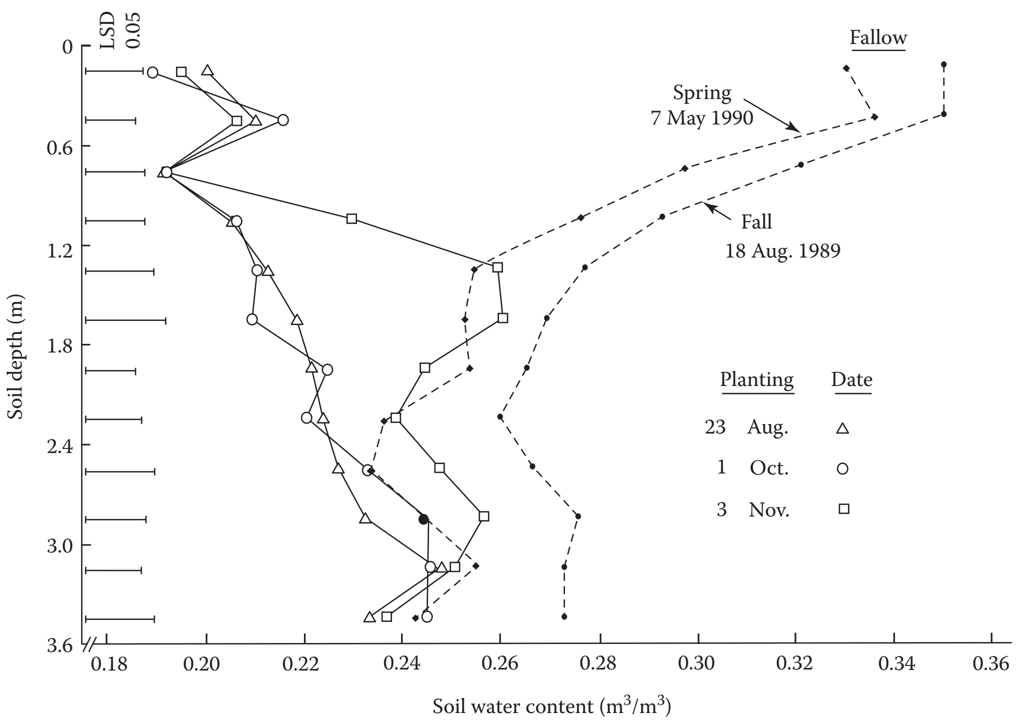

FIGURE 18.8 Soil water content near anthesis (May 7, 1990) for wheat at three planting dates (solid lines) and a fallow check plot on two dates (dashed lines). (From Winter, S.R. and Musick, J.T., *Agron. J.*, 85, 912–916, 1993.)

In the LSP, the range of seeding date for winter wheat is generally narrow because seeding normally occurs at the end of the rainy season. However, seeding date is still an important factor affecting yield and WUE (Chen et al. 1991; Shangguan 1998; Zhang 1998). Chen et al. (1991) reported that the optimum seeding date was in the middle of September (14–18). Either early or late seeding for just 1 day from optimum seeding date would reduce yield by about 150 kg/ha. The seeding date also interacts with N fertilization. For example, plants in early seeding were generally more responsive to N fertilizer than those in late seeding (Chen et al. 1991). The seeding rate in the LSP ranged from 150 to 200 kg/ha (Chen et al. 1991; Li et al. 2000; Huang et al. 2004) for both dryland and irrigated wheat. The seeding rate for dryland wheat is much higher than that in U.S. Great Plains.

In the SGP, early studies used wide row spacing (25–34 cm; Musick et al. 1994), while new studies generally used narrow row spacing (15 cm; Xue et al. 2010). When grown under conditions of relatively high yield potentials, narrow row spacing increased yields (Musick and Porter 1990). Seed quality can significantly affect wheat yield and WUE. Xue and Stougaard (2006) observed that spring wheat grown from large seeds generally had higher yield and WUE than those grown from small seeds. Growing large seeds significantly reduced soil evaporation (Xue and Stougaard 2006).

18.3.3 FERTILIZATION

Plant growth and development are dependent on soil nutrients supply. Improving nutrient status can significantly increase wheat yield and WUE. In both the U.S. SGP and the LSP of China, nitrogen (N) and phosphorus (P) are two major fertilizers applied for wheat production. The soils in both regions generally have sufficient potassium (K) (Musick and Porter 1990; Wang et al. 2011). Nitrogen is often the most limiting nutrient for wheat production and represents one of the highest input costs in agricultural systems (Thomason et al. 2002). Due to the semiarid environmental conditions, N fertilization had a significant interaction with soil water levels. In the SGP, Eck (1988) investigated the interaction of N and irrigation in wheat. The yield and WUE response to N fertilizer rates were largely related to irrigation frequency and water stress. For full irrigation treatment, yield and WUE increased as N rate increased up to 140 kg/ha. For limited irrigation treatments, 70 kg/ha was sufficient to obtain maximum yield and WUE. For dryland treatment, N had little effect on yield and WUE since yield was mainly limited by water stress. Nevertheless, wheat yield (2–3 Mg/ha) and WUE (0.45–0.65 kg/m^3) were low without N application under irrigated conditions. Application of N fertilizer increased yield to 5–6 Mg/ha and WUE to 1.03 kg/m^3. Among the yield components, application of N considerably increased spikes per square meter and seeds per spike but did not affect seed weight (Eck 1988).

In the LSP, application of N and P fertilizers has significantly increased wheat yield and WUE in the last three decades (Huang et al. 2003; Wang et al. 2011). Huang et al. (2003) and Wang et al. (2011) reported a long-term fertilization study in dryland winter wheat (1984–2009). Although yield and WUE varied from year to year due to precipitation variation, wheat with N and P fertilization always had higher yield and WUE. Without fertilization, yield was generally less than 2 Mg/ha and WUE was between 0.4 and 0.5 kg/m^3. Application of N (120 kg/ha) and P (60 kg/ha P_2O_5) increased the yield up to 4–5 Mg/ha and WUE to 1.4 kg/m^3 (Figure 18.9). Adding manure to N and P fertilizers also resulted in a higher yield and WUE (Wang et al. 2011). The main reason for increased yield and WUE by fertilization is that it promoted root growth and enhanced water use from soil water

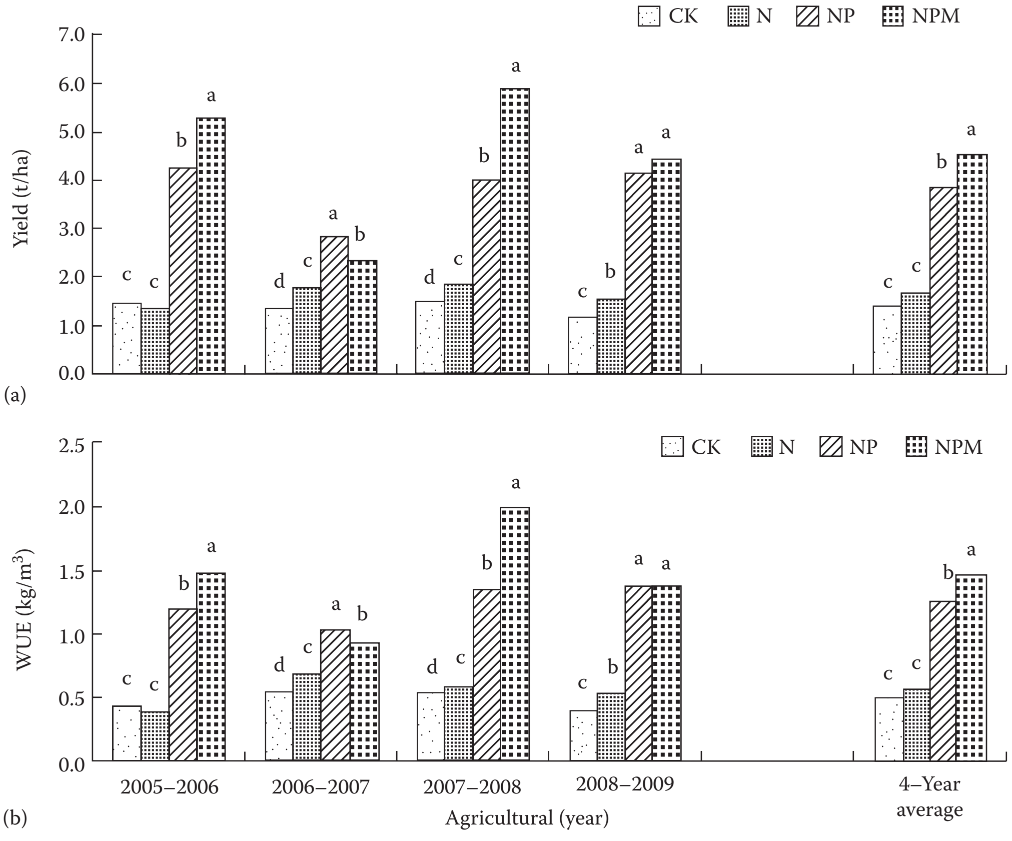

FIGURE 18.9 (a) Winter wheat yield and (b) water-use efficiency (WUE) in different fertilization treatments in a long-term fertilization study. (From Wang, J., Liu, W., and Dang, T., *Plant Soil*, 2011. DOI:10.1007/s11104-011-0764-4.) (CK: without fertilization; N: 120 kg/ha N; NP: 120 kg/ha N, 60 kg/ha P_2O_5; NPM: 120 kg/ha N, 60 kg/ha P_2O_5, and 76 Mg/ha manure.)

storage (Li and Su 1991). As a result, years of increasing fertilization combined with other yield-enhancing management practices have caused gradual depletion of soil water in the layer of 2–3 m profiles due to intensive plant water use (Li 2001; Huang et al. 2003). There is an increasing concern about the effect of current fertilization practices on sustainable wheat production and WUE in the region (Liu et al. 2010). On a regional scale, soil water conservation practices and intensive farming have induced soil water depletion, decreased surface runoff, and reduced movement of water into the soil profile (He et al. 2003). Although the amount of soil water storage was reduced, fertilization with N and P or with N, P, and manure significantly improved PSE and reduced soil water loss during the fallow period. Such improvement of PSE may offset some negative effects of low ASW at planting (Wang et al. 2011). Since manure application had positive effect on soil properties and wheat yield, manure should be included in fertilization practice for long-term sustainable wheat production (Wang et al. 2011). In addition, application of straw mulch may further improve wheat yield and WUE when combined with fertilization, particularly at high N rates (Gao et al. 2009).

Similar to the SGP, N and soil water had a significant interaction for wheat growth and yield in the LSP. In particular, plant response to fertilization was related to ASW at planting. Chen et al. (1991) showed that the application of fertilizers did not increase the yield when ASW at plant was lower than 330 mm in a 3-m profile. As ASW at planting increased from 330 mm, fertilizer application significantly increased the wheat yield. Xue and Chen (1990) showed that leaf photosynthetic rate and stomatal conductance in high N rates were more sensitive to water stress than those in low N rates. As such, wheat with higher N fertilizer rates may reduce yield under severe water stress. In a study in Australia, van Herwaarden et al. (1998) demonstrated that water deficit during grain filling reduced assimilation and consequently grain yield, and crops with high N rates suffered greater yield reduction than unfertilized crops. Since soil N availability is affected by many factors such as soil type, tillage system, crop residue, and rotation, the responses of wheat yield and WUE varied greatly (Zhang 1998). In addition, different cultivars also had different responses to N fertilization (Chen et al. 1991). Excessive N fertilizer application is not uncommon in LSP. For example, in some irrigated areas, N fertilizer rates averaged 450 kg/ha per year, that is, 225 kg/ha per crop (either wheat or corn) (Gao et al. 2009). High N fertilizer rates not only increase the risk to contaminate underground water but also may result in low N use efficiency (NUE) (Foulkes et al. 2009; Gao et al. 2009). Therefore, one future challenge for wheat production in the LSP is to improve NUE.

18.3.4 DEFICIT IRRIGATION

In the U.S. SGP, with the declining irrigation water supplies from Ogallala Aquifer and increasing energy costs, application of less irrigation water than the plants require for high yield will be the primary practice in the future for irrigated wheat production. Toward this end, deficit irrigation has been studied and practiced for over three decades and shown to be a viable management practice for improving yield and WUE (Eck 1988; Musick et al. 1994; Schneider and Howell 2001; Xue et al. 2003, 2006). Deficit irrigation is defined as the application of less water than is required for full ET and maximum yield, resulting in conservation of limited irrigation water and an increase in WUE (English 1990; Musick et al. 1994). Compared to dryland wheat, deficit irrigation significantly increased grain yield and WUE. In a field study in Bushland, Texas, deficit irrigation of 100 mm at booting stage increased the yield by 46% and WUE by 23% as compared to dryland treatment. Compared to full irrigation of 400 mm, a deficit irrigation of 220 mm at jointing and anthesis achieved 84% of the yield at full irrigation and resulted in 45% irrigation water savings (Table 18.2). In another study at the same location, Schneider and Howell (2001) showed that irrigation application of 50% ET requirement resulted in 86%–95% yield of full irrigation (100% ET). Deficit irrigation is an optimizing strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English 1990). Maintaining high ASW at planting is important for the successful practice of deficit irrigation for the efficient use of both precipitation

TABLE 18.2

Seasonal Evapotranspiration (ET), Biomass, Grain Yield, Yield Components, Harvest Index (HI), and Water-Use Efficiency in Yield (WUE) and in Biomass (WUE$_{bm}$) in Winter Wheat as Influenced by Irrigation

TRT	Total Irrigation (mm)	Seasonal ET (mm)	Biomass (Mg/ha)	Yield (Mg/ha)	Spikes (m^2)	Seeds per Spike	Seed Weight (mg)	HI	WUE (kg/m^3)	WUE$_{bm}$ (kg/m^3)
T-1	0	414e	10.4f	3.2f	674e	16.6d	29.2c	0.31c	0.782d	2.51b
T-2	100	498d	12.8de	4.6e	797abc	20.4bc	28.8c	0.36ab	0.933b	2.57ab
T-3	100	494d	14.0cd	4.7e	772bcd	21.3b	29.3c	0.34bc	0.958ab	2.84a
T-4	140	496d	12.6e	4.6e	730cde	18.5cd	33.8a	0.36ab	0.918bc	2.54b
T-5	140	427e	11.6ef	3.6f	688de	16.6d	31.8b	0.31c	0.842cd	2.72ab
T-6	220	604b	15.5b	6.0c	801abc	22.2b	33.7a	0.39a	0.992ab	2.57ab
T-7	220	547c	14.6bc	5.4d	756cde	23.0b	31.5b	0.37ab	0.993ab	2.69ab
T-8	300	686a	18.2a	6.7b	864a	26.9a	28.4c	0.37ab	0.973ab	2.65ab
T-9	400	691a	18.0a	7.1a	857ab	26.5a	31.8b	0.39a	1.030a	2.62ab

Source: Xue, Q., Zhu, Z., Musick, J.T., Stewart, B.A., and Dusek, D.A., *J. Plant Physiol.*, 163, 154–164, 2006.

In each column, different letters represented the significant difference at level of 0.05 based on the LSD test.

T-1: dryland; T-2–T-5: 1 irrigation at jointing (100 mm), booting (100 mm), anthesis (140 mm), and mid-grain filling (140 mm), respectively; T-6: 2 irrigations at jointing (100 mm) and anthesis (120 mm); T-7: 2 irrigations at booting (100 mm) and grain filling (120 mm); T-8: 3 irrigations at jointing (100 mm), booting (100 mm), and anthesis (100 mm); T-9: 4 irrigations at jointing (100 mm), booting (100 mm), anthesis (100 mm), and grain filling (100 mm); seasonal precipitation: 254 mm.

and irrigation water (Musick et al. 1994). Xue et al. (2003) demonstrated that high ASW at planting resulted in deep root system and could delay the irrigation until anthesis if only one irrigation was allowed. When only a limited amount of irrigation is available, irrigation must be applied at critical stages for wheat yield determinations. Critical growth stages for irrigating winter wheat generally occur from early spring growth (floral initiation) to early grain development (Musick et al. 1994; Schneider and Howell 2001). Xue et al. (2006) examined the physiological mechanisms that contributed to increased yield and WUE under deficit irrigation. The increased WUE was largely related to an improved HI in different irrigation treatments (Figure 18.7). The HI is determined during grain filling by both current photosynthesis and remobilization of preanthesis carbon reserve from stems. For the maintenance of current photosynthesis to meet the carbohydrate supply, higher photosynthesis rate and longer green leaf area duration are advantageous under drought conditions. When the photosynthesis during grain filling is reduced by drought or heat stresses, the remobilization of carbon reserves can be important to grain filling. The contribution of remobilized carbon reserves to grain yield in wheat varied from 5% to 90%, depending on environmental conditions (Foulkes et al. 2002; Asseng and van Herwaarden 2003; Xue et al. 2006). The increased HI under appropriate deficit irrigation was due to both increased current photosynthesis and the remobilization of preanthesis carbon reserves (Xue et al. 2006).

Although winter wheat is grown mainly under dryland conditions in the LSP, irrigation is still possible in some areas with limited water resources. A small amount of irrigation at critical stages can significantly increase yield and WUE as compared to dryland. Fan et al. (2005a) reported a 3-year study with different amounts of supplementary irrigation (12–48 mm) at various stages (tillering, jointing, booting, and heading). Although yield varied due to precipitation, supplementary irrigation always increased yield as compared to dryland. The supplementary irrigation significantly increased WUE. For example, 36 mm irrigation at jointing stage resulted in a WUE of 2.17 kg/m^3 as compared to a WUE of 1.07 kg/m^3 in dryland treatment (Fan et al. 2005a). Based on a long-term field study, Huang et al. (2004) demonstrated that three irrigations (87.5 mm) at jointing, booting, and anthesis resulted in high yield and WUE as compared to dryland. However, one irrigation (87.5 mm) at booting stage still resulted in 78% yield of full irrigation treatment (four irrigations) and 75% of water savings (Huang et al. 2004). Kang et al. (2002) demonstrated that increased yield and WUE under limited irrigation conditions were largely related to improved HI, which is similar to findings from Xue et al. (2006) and Zhang et al. (1998). In the Northern China Plain, Zhang et al. (1998) showed that one irrigation at booting stage produced comparable yield and resulted in 24%–30% WUE increase as compared to four-irrigation treatment. The increased WUE was contributed by deep root system and higher HI.

In the SGP, irrigation technology has changed significantly in the last four decades, from furrow irrigation in the early years (1950s–1970s) to the current central pivot sprinkler systems (Musick et al. 1990; Colaizzi et al. 2008). The subsurface drip irrigation (SDI) system has also been used in the region in recent years. Over the years, irrigation efficiency has improved significantly (Howell 2001; Colaizzi et al. 2008). However, with the declining trend of well capacities in many areas, the future challenge will be to efficiently use reduced amount of irrigation in central pivot systems. SDI systems may have some advantages over central pivot for delivering small amounts of irrigation water. In the LSP, the traditional irrigation system is furrow flood irrigation. Although some new irrigation technologies (e.g., water delivered with low pressure pipes, and sprinkler and drip irrigation) have been tested and proved to be more efficient than furrow irrigation, these technologies have not been widely advocated or adopted (Deng et al. 2006).

18.4 FUTURE PERSPECTIVES

Although progress has been made to improve wheat yield and WUE in the last few decades in the U.S. SGP and China's LSP, the current WUE level is still below the generally accepted upper limit (2.0 kg/m^3) in most cases, particularly in the SGP. As such, developing better management strategies is still a challenge for agricultural scientists. In both regions, ASW at planting is extremely important to increasing wheat yield and WUE. For dryland wheat production in the SGP, management practices (e.g., NT, residue mulching, and rotation) resulted in significant gain in soil water storage during the fallow period. Future research must address how to efficiently use limited growing season precipitation (Stewart et al. 2010). Soil water is critical for yield during late developmental stages (e.g., from booting to anthesis) for grain production. Therefore, one important challenge is to save soil water from early season precipitation for use during the critical grain production period (Stewart et al. 2010). Using relatively lower seeding rate and optimum seeding date may provide some benefits to manipulate plant water use. However, highly variable seasonal precipitation makes it difficult to draw a general conclusion. The amount, intensity, and timeliness of precipitation during the growing season are often so erratic that successful practices for one year often fail in subsequent years.

Since the drought stress is inevitable during the wheat-growing season, improving drought resistance through breeding will be an important part of overall crop improvement. Currently, breeders are not well equipped to make selections in drought resistance because information is lacking on (i) the extent of variation for drought resistance within elite germplasm; (ii) key physiological and morphological traits that contribute to drought resistance, WUE, and yield determination; and (iii) genetic factors that control these traits, and empirical and molecular tools for selection of superior germplasm in breeding programs (Ober 2008). A better understanding of crop response to drought stress and identification of plant traits will lead to the development of improved germplasm and cultivars in the region. Improving transpiration efficiency (TE, or WUE$_{bm}$) has been successful for increasing yield and WUE in Australia (Richards et al. 2002, 2010). In the SGP, genetic variability of TE has been found in sorghum (Balota et al. 2008; Xin et al. 2008, 2009). However, the genetic variation in TE among wheat genotypes has not been well understood and needs to be investigated in future research.

The declining irrigation water continues to challenge the irrigated wheat production in the SGP. Although several management factors (improved cultivars, fertilization, pest control, etc.) contributed to wheat yield and WUE improvements, irrigation played a vital role in increasing wheat yield and WUE in the region. Irrigated wheat yields can be two to four times higher than dryland yields (Figure 18.3; Howell 2001). Therefore, irrigation will be an important management practice for a long time. Since irrigation water is becoming limited, deficit irrigation will be the primary practice in the future for irrigated wheat production. Toward this end, the adoption of drought-resistant cultivars is also important for implementing the deficit-irrigation practice.

In the LSP, the future wheat production will likely be dependent on dryland production because of the very limited irrigation resources. Since the majority of precipitation falls in the wheat fallow period, improving PSE becomes extremely important. Currently, the PSE level is generally low (<40%) and varies from year to year (Shangguan et al. 2002; Jin et al. 2007; Wang et al. 2011). Therefore, the future research must address how to increase PSE. Traditionally in the region, wheat straw has been harvested by farmers for various purposes and the field is deep-plowed after harvest for improving precipitation infiltration (Shangguan et al. 2002). Recent studies indicated that leaving the straw as a mulch combined with NT significantly increased PSE (Jin et al. 2007). Proper fertilization also increased PSE (Wang et al. 2011). Currently, the cropping and rotation systems in the LSP are not diversified and CW is still a dominant cropping system. Using diversified cropping and rotation systems may provide opportunities to increase PSE, PUE, and total crop yield in the future. For example, Li et al. (2002) demonstrated that winter wheat–legume–summer crop was a viable rotation system to increase overall PUE. The future improvement of PSE and PUE may be dependent on the integration of various management practices such as straw mulching, RT, and fertilization, and adopting more diversified cropping systems. The N and P fertilization has played and will continue to play an important role in increasing wheat yield and WUE in the region. There are two major challenges for maintaining long-term benefits of fertilization. First, long-term application of chemical fertilizers and unbalanced fertilization may result in low soil fertility and soil organic carbon (SOC) (Fan et al. 2005b). Combined chemical fertilizers and organic materials (either crop residues or manure) will not only result in sustainable crop productivity but also increase SOC, which provides numerous environmental benefits. Second, excessive application of N fertilizer is a common practice in the LSP. As such, future research is needed to address NUE under various N fertilizer rates.

ABBREVIATIONS

ASW	Available soil water
BM	Biomass at maturity
CT	Conventional tillage
CW	Continuous wheat
ET	Evapotranspiration
HI	Harvest index
LSP	Loess Plateau
NASS	National Agricultural Statistical Service
NT	No-till
PSE	Precipitation storage efficiency
PUE	Precipitation use efficiency
RT	Reduced tillage
SGP	Southern Great Plains
SS	Subsoiling with mulch
TC	Two crops per year
TE	Transpiration efficiency

WF	Wheat–fallow
WSF	Wheat–sorghum–fallow
WUE	Water-use efficiency in grain yield
WUE_{bm}	Water use efficiency in biomass.

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Section V

Policy and Economics

19 Sustainable Land and Water Management Policies

Claudia Ringler and Ephraim Nkonya

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19.1 INTRODUCTION

A critical challenge for agriculture over the next half century is to increase food production within the constraints of scarce land and water resources and overused soils—conditions that are growing in severity in many parts of the world. While difficult to measure, land (including soils) and water constraints may easily reduce the food production potential by 5%–10% today and 20% by 2025. For example, Rosegrant et al. (2002) estimated—for the group of developing countries—the loss of cereal production potential as a result of growing water scarcity over time to 2025, and in 2008, they expanded their estimates to 2050 (Figure 19.1). While in 1995 about 5% of developing-country grain production potential was lost as a result of water scarcity, by 2025 this share is expected to increase to 11% of potential production and by 2050 to 14% of global cereal production. At the same time, land degradation remains one of the major challenges to food production. A recent study shows that 24% of the global land area is degraded (Bai et al. 2008). The largest degraded areas are concentrated in Africa, south of the equator, which account for 13% of total degraded area (Bai et al. 2008). The same study also showed a positive correlation between land degradation and infant mortality, suggesting a positive relationship between poverty and land degradation. Estimates of the cost of land degradation vary widely. Requier-Desjardins (2006) suggests that land degradation in Africa leads to a loss of 3%–9% of agricultural gross domestic product (AGGDP), a loss that underscores the importance of land degradation in developing countries. To reduce growing water

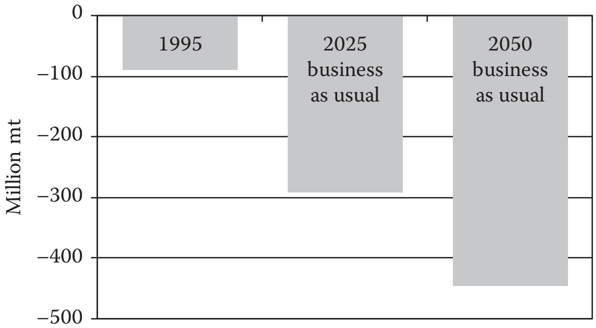

FIGURE 19.1 Loss of grain production potential due to water scarcity in developing countries. Loss of production potential refers to the grain quantity that could not be produced as a result of lack of water availability. (From Rosegrant, M.W., Cai, X., and Cline, S.A., World water and food to 2025: Dealing with scarcity. Joint publication. Washington, DC, and Colombo, Sri Lanka: International Food Policy Research Institute and International Water Management Institute, 2002; IFPRI IMPACT simulations (2008).)

and land shortages is partly a technical problem, but much more so a challenge of better policies, rights, and institutions.

Appropriate policies, rights, and institutions are key ingredients for sustainable land and water management (SLWM). They can provide incentives to users for appropriate use based on the scarcity value of the resource and for investing in land and water resource conservation. However, land and water management policies have been slow to adjust to the rapid pace of economic change of the last few decades and are generally inadequate to address growing land and water challenges. As a consequence, in many parts of the world, the resources are unnecessarily degrading, and particularly so in the group of developing countries. One way to enhance policy outcomes for both water and land could be through the development of policies that take account of the growing scarcity of both resources and their interrelationships in a holistic fashion, at least in cases of important synergies (Binswanger-Mkhize et al. 2011).

The focus of this chapter will be on policies and institutions that directly impact land and water outcomes. However, we acknowledge that there are a host of policies and institutions in the agriculture and nonagriculture sectors with potentially large positive and negative impacts on land and water resources. An assessment of the entire scope of global, regional, and national policies that can affect land and water outcomes is, however, outside the scope of this chapter.

19.2 CHALLENGES TO SUSTAINABLE LAND AND WATER MANAGEMENT

A key challenge to SLWM remains the continued need to increase food supplies—for a population estimated at 9 billion by 2050, up from 6 billion in 2000. Growth of incomes and urbanization are leading to shifts in consumer demand toward food products that are more water-intensive. On the supply side, investments in land and water are expected to increase only slowly and at growing costs, leading to continued degradation of the land and water base. Distorted macroeconomic and trade policies will continue to favor food production and natural resource extraction in some areas without comparative advantage. Moreover, agricultural input and output price subsidies and other distorted incentives in many countries further degrade land and water resources, contributing to groundwater depletion and poor fertilizer application practices in much of South Asia. Moreover, overgrazing of fragile pastures and grasslands is common in many parts of the world.

On the demand side, over the last several decades, competition from industrial, household, environmental, and aquaculture water uses has significantly increased challenges for water resource management for agriculture. In addition to adverse impacts on agricultural economies, industrial and household uses often return poor-quality water to the environment and irrigation, particularly in developing countries, with potential adverse impacts on the productivity, health, and environment of farmers, crops, livestock, and fisheries (Meinzen-Dick and Ringler 2008; Rosegrant and Ringler 1998).

On the land side, expanding cities continue to absorb small, but highly productive lands. Indonesia, for example, has documented encroachment of housing, industrial estates, and other economic infrastructure of around 1 million hectares on agriculture land between 1983 and 1993 on Java alone (BPS, Agriculture Census 1993). Importantly, biofuel production using sugarcane or corn and other feedstocks has diverted significant areas of land away from food production and increasingly threatens sustainable land, soil, and water use in addition to food prices and thus affordability for the poor. Higher energy prices have also increased the costs of intensive agricultural production—which had helped reducing deforestation.

Thus, after decades of being considered of little or no interest to both policymakers and investors, the food price crisis of 2005–2008 brought the need for investments in sustainable land and water resources back to the forefront; but the subsequent financial crisis and the ensuing (short-term) drop in food prices have somewhat dampened renewed interest.

19.2.1 GROWING SCARCITY OF LAND AND WATER RESOURCES

While irrigation water supply is expected to increase slowly, nonirrigation demands are expected to double out to 2050, putting pressure on supplies available for irrigation, particularly in the group of developing countries where changes in population, economic growth, and urbanization are fastest. Some nonirrigation and nonagricultural land-use demands will come at a direct cost to agriculture, particularly in countries with high economic growth coupled with limited natural resources, such as China, and countries with extreme water scarcity, such as the Middle East and North Africa.

Irrigated harvested area—taking multiple cropping and estimates of informal irrigation into account—is expected to increase from 421 million hectares in 2000 to 473 million hectares by 2050 at 0.23% per year. As has been stated earlier, water scarcity alone has already reduced the cereal production potential in the mid-1990s and is expected to account for a larger loss of potential in the future, even without taking into account adverse impacts from climate change and further land degradation (Rosegrant et al. 2002; IFPRI IMPACT Simulations 2008). Another measure of growing water shortages for agriculture is the irrigation water supply reliability index (IWSR), which measures the availability of water relative to full water demand for irrigation. This index is projected to decline from 0.71 globally in 2000 to 0.66 by 2050 (IFPRI IMPACT Simulations 2008), with steeper declines in water-scarce basins. Furthermore, irrigators are hurt not only on average but because water availability becomes more susceptible to downside risk in low rainfall years. In much of the world, the problem will be compounded by increasing intra-annual variability in rainfall and significant increases in the number and severity of droughts (Meehl et al. 2007).

Agricultural harvested area is estimated to grow only at 0.39% annually from 2000 to 2025 and 0.07% per year during 2025–2050; productivity growth in much of current rainfed agriculture could be significantly higher if the challenges of turning low-potential areas into high-potential areas could be overcome in much of sub-Saharan Africa, parts of Latin America, and parts of the former Soviet Union. These challenges include poor infrastructure, poor access to markets, and lack of incentives for small farmers and investors alike. Of course such conversion will need to take into account environmental and carbon sequestration needs and opportunities. Per capita land area has been falling rapidly in sub-Saharan Africa but also in Latin America and the Caribbean and South Asia. Per capita arable area declined from 0.5 ha per capita to 0.25 ha per capita from 1970 to 2005 (Figure 19.2). Per capita arable land area in the East Asia and Pacific region was smallest throughout but it maintained a stable trend over the 30-year period. Decreasing land area leads to conversion of forest lands to agriculture and expansion of crop production into more fragile areas, which in turn leads to more severe land degradation.

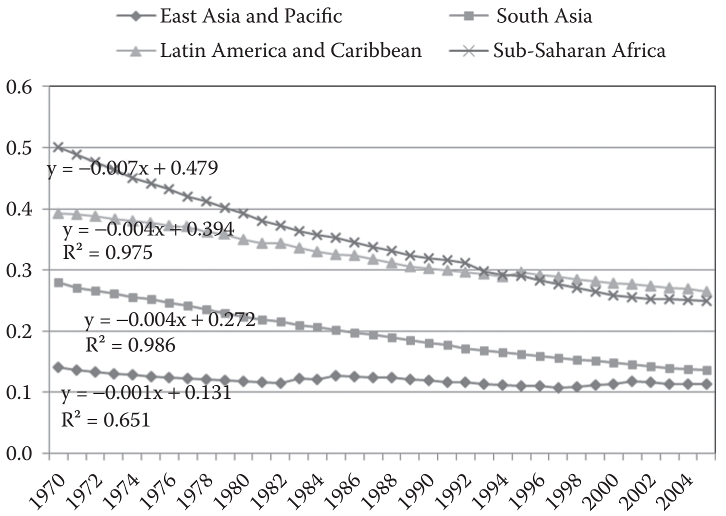

FIGURE 19.2 Trend of per capita arable land area in developing countries. (From FAOSTAT [FAO Statistical Databases], 2010. Accessed online at http://faostat.fao.org/.)

In conclusion, growing scarcities of water and land are projected to increasingly constrain food production growth, causing adverse impacts on food security and human well-being goals and were an underlying factor of the food price spikes during 2005–2007.

19.2.2 Increasing Competition for Nonfood Uses (Including Biofuels)

The production of biofuels affects land and water resources in two ways: directly through land reallocation from food to nonfood crops and water withdrawals for irrigation and the industrial processes of feedstock conversion; and indirectly by increasing water loss through evapotranspiration that would otherwise be available as runoff and groundwater recharge (Berndes et al. 2003). Biofuel production can also affect water quality by increasing nutrient loads in rivers and lakes and by accelerating soil erosion. Even though globally the amount of water withdrawn for the production of biofuels is modest, local water scarcity problems may worsen due to the irrigation of feedstocks or when rainfed feedstocks have higher evapotranspiration requirements than previous land uses. It is unlikely that investors in large-scale biofuel plantations would rely on rainfall only to support their investments (Rosegrant et al. 2008). In countries with little land and water available for biofuel expansion, the use of water for biofuel production is likely to affect existing water allocation both across sectors as well as within agriculture and can involve serious trade-offs between energy, environment, food security, and livelihood protection (McCornick et al. 2008; Muller et al. 2008). Rosegrant et al. (2008) show that continued rapid expansion of biofuel production will have significant impacts on the food sector. Under a "biofuel expansion" scenario, 2020 world prices are 26% higher for maize, 18% higher for oilseeds, 12% higher for sugar, 11% for cassava, and 8% for wheat compared with the 2020 prices in the baseline scenario, presenting a clear "food-versus-fuel" trade-off. These impacts include substantial price increases for food commodities, reductions in the availability of calories, and increased levels of malnourishment at the regional level, particularly in sub-Saharan Africa. Careful land and water-use planning focusing on rainfed and marginal land and water-using feedstocks, such as sweet sorghum and Jatropha, could help mitigate some adverse impacts (McCornick et al. 2008).

Moreover, second-generation biofuels will still require water and land resources and, importantly, access to rural infrastructure that is generally poorly developed in countries with potential for area expansion, such as parts of sub-Saharan Africa and Latin America. To ensure sustainable development of biofuels without undue impact on land and water resources will require sound water and land policy and right systems that reveal the full set of costs and benefits of biofuel developments; these are described in detail in the following sections.

There have also been significant efforts to develop pharma plants using maize and tobacco particularly since the 1990s; but so far transgenic pharma crops have not gone forward as a result of regulations, the cost of development, and commercialization, as well as possible market and litigation risks in the United States. Producing pharma crops in open fields requires a full segregation and aiming for zero percent tolerance for comingling, which may be tricky, particularly for crops like maize (Guillaume Gruere, personal communication).

19.2.3 DEGRADATION OF THE WATER AND LAND BASE

Major land and water degradation processes include the degradation of water and soil in irrigated areas, the depletion of groundwater, the degradation of water-related ecosystems, increasing water pollution, desertification processes, the growing overgrazing of pasture lands, and the depletion of agricultural soils in rainfed and dryland areas, especially in sub-Saharan Africa. Issues are more severe in sub-Saharan Africa because of a lack of rural infrastructure and availability and access to other agricultural inputs. In much of the rest of the world, degradation of irrigation infrastructure investments is proceeding apace, increasing the need for modernization and rehabilitation. Similarly, agrochemical pollution, overgrazing, soil nutrient depletion, and degraded soils require significant investments for sustainable soil and land management.

Poor irrigation practices accompanied by inadequate drainage have often damaged soils through oversaturation and salt buildup. A notable example is the Aral Sea Basin in Central Asia, which shrank drastically as a result of excessive withdrawals for irrigation. It is estimated that on a global scale there are about 20–30 million hectares of irrigated land severely affected by salinity. The global annual losses due to salinity are estimated to be US$12 billion (Pitman and Läuchli 2004). An additional 60–80 million hectares are affected to some extent by waterlogging and salinity (FAO 1996). In arid and semiarid areas, pumping groundwater at unsustainable rates has contributed to significant lowering of groundwater tables, particularly in South Asia and in parts of China, but also in parts of the United States, and to saltwater intrusion in some coastal areas (Vorosmarty et al. 2005).

19.2.4 GROWING POLLUTION OF WATER AND LAND

Growing water pollution is a further constraint to SLWM. Poor water quality increasingly constrains agricultural and economic development in regions that experience water scarcity and are plagued by poor wastewater treatment, particularly in densely populated Asia. Water pollution reduces agricultural production and threatens fish and other aquatic life and human health. Agrochemical pollution as a result of poor nutrient management practices is a growing concern in much of East and Southeast Asia, parts of the former Soviet Union, and some plantations in Central and Latin America. Subsidies for agrochemicals, poor extension services, and lack of water quality monitoring and enforcement of existing standards are the cause for much of today's agrochemical pollution. China clearly leads in this type of pollution, consuming more than 30% of the world's nitrogen fertilizer, which is applied to only 7% of the world's agricultural area (FAOSTAT 2010).

Biological and industrial nitrogen fixation converts about 120 million tons of nitrogen annually (Rockström et al. 2009) but about two-thirds of the fixed nitrogen finds its way to waterways (Corcoran et al. 2010). Nitrogen runoff causes eutrophication in lakes and pollution of coastal reefs at river mouths, both of which have severe impacts on fish stock and human health. Similarly, about 10 million tons of phosphorus is deposited in water globally (Corcoran et al. 2010). Improved fertilizer use efficiency could reduce this pollution and save both costs and pollution. Unfortunately nutrient use efficiency technologies have not been widely promoted in developing countries. They include optimizing the timing of fertilizer application, split application, soil testing, balanced nutrient application, and use of crop varieties with a strong response to fertilizer application (Roy et al. 2002).

Freshwater biodiversity and associated fisheries are on a decline in almost all developing countries with negative impacts on protein availability for the poor. Rapid economic growth in Asia is increasing political pressures to remedy these pollution efforts, and the induced policy and institutional changes will eventually lead to reductions in pollution, as they have in most of the developed world (Lomborg 2007).

19.2.5 CLIMATE CHANGE IMPACTS ON LAND AND WATER FOR AGRICULTURE

The principal water-related climate changes include changes in the volume, intensity, and variability of precipitation and higher crop water evapotranspiration needs as a result of higher temperature. Increases in precipitation are mainly expected in high latitudes while decreases are expected in subtropical and lower latitude regions (Bates et al. 2008). Furthermore, rising temperatures will increase the rate of snow cap and glacier melt, affecting agricultural production in river basins fed by mountain ranges. Sea-level rise due to the thermal expansion of seawater and the melting of continental glaciers will lead to inundation of low-lying coastal areas, with significant adverse effects, including salinization of coastal agricultural lands, damage to infrastructure, and tidal incursions into coastal rivers and aquifers (Kundzewicz et al. 2007).

Analyses of multiple climate change scenarios indicate that climate change will likely have a slight to moderate negative effect on crop yields (Parry et al. 2004; Cline 2007; Nelson et al. 2009), and crop irrigation requirements would increase (Frederick and Major 1997; Doll 2002; Fischer et al. 2006), as would overall water stress in many areas dependent on irrigation (Arnell 1999; Fischer et al. 2006). Nelson et al. (2009) estimated that irrigation and water-use efficiency will account for about 42% of the estimated US$7.3 billion annual investment required to reduce childhood malnutrition to a level without climate change.

19.3 POLICIES, INSTITUTIONS, AND INVESTMENTS FOR SUSTAINABLE LAND AND WATER MANAGEMENT

There is not one “optimal” institutional arrangement for water or land; rather, it is critical to understand the potential contributions, facilitating conditions, and limitations of each (Merrey et al. 2007; Meinzen-Dick 2007).

19.3.1 THE NEED FOR DEMAND MANAGEMENT FOR WATER

In the past, increasing the supply of water through new water development has been a common strategy to manage water resources. However, in maturing water economies, which are characterized both by increasing scarcity of water (Randall 1981) and by increasing transfers of water both in scale and amount, managing the demand for water becomes more important. The task of demand management is to generate both physical savings of water and economic savings by increasing the output per unit of evaporative loss of water, by reducing water pollution, and by reducing nonbeneficial water uses. Bhatia et al. (1995) differentiate four types of policy instruments for demand management: (1) enabling conditions, which are actions to change the institutional and legal environment in which water is supplied and used, such as policies of development of institutions, water rights and collective action mechanisms, and water user associations, but also the privatization of utilities; (2) market-based incentives, which directly influence the behavior of water users by providing incentives to conserve water use, including water pricing, water markets, as well as effluent charges and other taxes and subsidies; (3) nonmarket instruments, such as quotas, licenses, and pollution controls; and (4) direct interventions, such as investments in efficiency-enhancing water infrastructure, or conservation programs. The specific set of water policies that will be used varies from location to location depending on the status of economic development, the level of water scarcity, historic development, and institutional capability. In most situations, a mix of all four types of policy instruments is applied. Despite the wide range of water policies, implementation remains generally rather complex, given the variety of sources, ranging from precipitation to groundwater, and various surface water bodies, the fluidity of the resource, the many claimants on its uses, and the distinction between consumptive and nonconsumptive uses.

19.3.2 Complexities in Water Management

Moreover, water policies are implemented at different scales, ranging from the local level to the district, national, and regional levels up to the global level. While most statutory-based water policies are generated at the national level, increased decentralization processes have moved the actual implementation and applications to lower levels of authority, in particular, the province or district level—providing both new opportunities and new challenges (e.g., in Indonesia). At the same time, some water and related policies have moved up to higher levels, such as global climate policy, which is being discussed by the United Nations Framework Convention on Climate Change (UNFCCC) and assessed by international working groups, such as the Intergovernmental Panel on Climate Change (IPCC). Moreover, water policies can also be implemented at the basin boundary or subcatchment level, which tends to dissect various administrative scales. Furthermore, some water policies follow customary use rights, generally those on a small scale, while others are based on statutory laws and regulations. Thus, multiple legal and normative frameworks coexist, and the dynamics between statutory and customary water policies are fluid and in constant motion (see also the literature on legal pluralism, e.g., Bruns and Meinzen-Dick 2000).

As a further complexity, in many countries, including both developed and those in development, water policies are developed and implemented by different agencies or ministries, including those focusing on the environment, agriculture, public health, construction, energy, fisheries, and water proper. In addition to fragmentation across agencies, the source itself is often fragmented across different agencies with surface water sources managed separately and by agencies that differ from groundwater sources.

19.3.3 Water and Land Rights as the Foundation for Sustainable Management

The key basis of sustainable water policy is water rights. Although some system of water rights is found to operate in virtually any setting where water is scarce, systems that are not firmly grounded in formal or statutory law are likely to be more vulnerable to expropriation. On the other hand, if well-defined rights are established, the water user can benefit from investing in water-saving technology. Growing water scarcity and the possibility to exclude other users has led the trend to the establishment of private property rights to water. Trends have been similar for land, where private property rights are most common (Bruns and Meinzen-Dick 2000, 2005; Rosegrant and Binswanger 1994; Binswanger-Mkhize et al. 2011).

Improvement in land tenure systems would enhance the enforcement of agricultural land preservation and promote sustainability objectives. Rural populations under weak land preservation regulations have failed to invest in long-term land improvements on existing agricultural land and have also, in many countries, abandoned land in favor of migration to forest and other marginal lands. Policies related to land tenure and resources access are of great relevance for the sustainable management and use of natural resources in all countries of the world where the majority of the population relies heavily on land to provide income, employment, and livelihoods. In recent years, there is a growing recognition of the centrality of the land tenure in sustainable development processes as witnessed by new land policies and increasing local and international demands for relevant and sound land tenure laws and regulations (Rosegrant et al. 2009).

When property rights are difficult to define or enforce, as for example for common pool resources, such as small reservoirs or communal forest lands, collective action is needed to achieve sustainable water management (Ostrom 1990). While scarcity itself and access to markets may drive the emergence of collective action and/or property rights, appropriate institutions are needed to enable and administer property rights and to support collective action. If property rights to water or land have not been established by statutory means or if customary rights are not recognized by government authorities, local water users might lose out when biofuel plantations are established through government sales of concessions.

While private property rights are increasingly important, the need for enhanced state capacity for water and land management is increasing as well as a result of growing challenges of water scarcity and competition. For water, state capacity is increasingly needed to coordinate water users across systems and across sectors, bridging between irrigation, municipal, industrial, and environmental uses and users and between water quantity and quality. For land, state capacity is needed to register land titles and enforce land rights (Binswanger-Mkhize et al. 2011).

19.3.4 Economic Incentives for Land and Water Management

Economic incentives for water management include prices, taxes, subsidies, quotas, and ownership/rights. These incentive measures, when implemented appropriately, can affect the decision-making process and motivate water users to conserve and use water efficiently in irrigation and other uses. Economic incentives play out differently under differing enabling institutions. The most important among these enabling institutions are water rights for farmers and other water users. Other institutions that influence economic incentives include the rule of law and good governance, the relative focus on public systems versus private development, the role of decentralization in the form of farmer management of irrigation systems, and the existence or not of river basin organizations.

Water pricing is the most common economic instrument used. In a review of the World Bank irrigation and drainage portfolio covering 68 projects, water pricing was most common (52 out of 68 projects) (Dinar 2001). However, prices are generally far below full capital cost recovery in both the developing and the industrialized countries (OECD 1999; Dinar and Subramanian 1998; Barker and Rosegrant 2007). At the zero or low levels of current irrigation water prices in many countries, irrigation water use is highly price inelastic; and prices high enough to induce significant changes in water allocation (or recover capital costs) would severely reduce farm income (Ringler 2005; Perry 2001; Löfgren 1996). However, water pricing policies can improve efficiency and sustainability when combined with appropriate supporting policies (Rosegrant et al. 1995; Dinar and Mody 2004; Gardner 1983).

For many developing countries facing high water scarcity and rapid urban-economic growth, paying farmers for using less water can be an attractive alternative that supports rural-to-urban water transfers while providing compensation to long-term irrigation water users. If adequately compensated, irrigators can then invest in on-farm advanced irrigation technologies and/or switch to less-water-consuming crops (Rosegrant et al. 2005).

Water markets can also provide important economic incentives. They empower water users, by requiring user consent to any reallocation of water and by compensating users for water transferred. Thus, marketable rights induce water users to consider the full opportunity cost of water, including its value in alternative uses, thus providing incentives to economize on the use of water and gain additional income through the sale of saved water. Finally, a properly managed system of tradable water rights provides incentives for water users to internalize the external costs imposed by their water use, reducing the pressure to degrade resources (Rosegrant and Binswanger 1994).

19.3.5 SUSTAINABLE LAND MANAGEMENT

Land and water used for agricultural production have complex and inseparable linkages suggesting benefits from joint management (Bossio et al. 2007; Binswanger-Mkhize et al. 2011). With the advent of climate change, this linkage has become even more imperative, especially in dry and humid areas.

For land resources, studies have shown that integrated land management practices that strategically integrate organic and inorganic fertility management practices lead to higher and sustainable yields (Vanlauwe et al. 2010; Tittonell et al. 2008) and were found to be more profitable than practices that use either one of the two alone in Africa (Doraiswamy et al. 2007; Tschakert 2004; Sauer et al. 2007; Nkonya et al. 2009). Box 19.1 provides an example from Nigeria, showing high returns of joint fertilizer and manure management but low adoption.

Despite the high returns to sustainable land management (SLM) practices, their adoption rates have remained low due to the their high labor intensity, limited extension services promoting integrated soil fertility management practices, and poor rural services supporting efficient marketing (Sauer et al. 2007; Pender 2009; Nkonya et al. 2009). The results suggest the need to use multipronged approaches to address the current land degradation and the low adoption of SLM practices. Consistent with Boserup (1965), for example, a long-term study by Tiffen et al. (1994) showed “more people, less erosion” in Machakos, Kenya, an area with better market access to market. Similarly, a recent study also showed a negative correlation between population density and land degradation (Bai et al. 2008). These results suggest that in areas with high market access and other favorable agricultural policies, farmers use SLM practices successfully (Boyd and Slaymaker 2000; Mazzucato and Niemeijer 2001).

BOX 19.1 BENEFIT–COST ANALYSIS OF NIGERIA LAND MANAGEMENT PRACTICES

A study was done in Nigeria to determine the costs and benefits of a combination of land management practices including manure, fertilizer application, and incorporation of crop residues. Using 30-year crop simulation data and household survey data, the study showed that a combination of crop residues (100%), manure (5 tons/ha), and fertilizer (80 kgN/ha) gave higher returns than those which use one of the three treatments alone (Nkonya et al. 2009). However, household survey data showed that the adoption of the most profitable land management practice (combination of fertilizer, manure, and crop residues) was only 8% compared to 18% for manure alone and 31% for fertilizer alone (Figure 19.3).

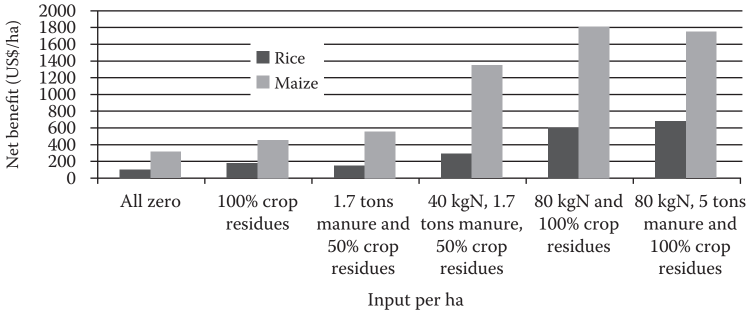

FIGURE 19.3 Returns to integrated soil fertility management practices for maize and rice in Nigeria.

These favorable findings are not universal, however. Other studies have shown more severe land degradation in densely populated areas (e.g., Cleaver and Schreiber 1994). In such cases, market failure and other unfavorable policies have been the major challenges for adopting SLM practices.

19.3.6 Increasing Crop Yields

Increasing crop yields, for example, through closing the yield gap between developed and developing regions and between rainfed and irrigated crops can save significant water resources and help conserve ecosystems and remaining forest areas in the developing world. Breeding strategies in the past have focused on crop yield enhancement. More recently, the focus has been on increasing stress tolerance, particularly drought resistance, allowing crops to survive in warmer, water-scarcer environments. Other important water- and land-saving research strategies include increasing the nitrogen use efficiency of fertilizers and range from zero-till systems that conserve soil moisture and help sequester carbon to laser-leveling systems for optimal agricultural input use. To support the development and adoption of new technologies requires not only profitability at the farm level but also a supportive national agricultural research and extension system, intellectual property rights protection, and the existence of efficient agricultural input and output markets (Rosegrant et al. 2009).

19.4 CONCLUSION

Growing scarcity of water and land is projected to progressively constrain food production growth, slowing progress toward food security and goals of human well-being. In the absence of institutional, policy, and investment reform, water and land for food production will increasingly conflict with other uses and users in many parts of the world. Negative impacts will be even more pronounced under climate change, especially in developing countries. Even under moderate climate change scenarios, impacts are projected to be negative for dryland areas in Africa, Asia, and the Mediterranean. Increasing water scarcity for agriculture not only limits crop area expansion but also slows irrigated cereal yield growth in developing countries. Similarly, increasing land diversion for nonfood crops, and urban and industrial encroachment, as well as continued loss to degradation will slow agricultural productivity growth.

Joint land and water management has been attempted in pastoral systems and in watershed management, but the time frame for implementation is generally very long and there are few successful cases. Addressing land and water degradation can benefit from a watershed approach, including problem identification, land-use planning, and institutions for coordinating between upstream and downstream areas. Integrated land and water management through watershed rehabilitation has been successful in China's Loess Plateau area, for example (World Bank 2003, 2007).

Payment for Environmental Services (PES) has increased in importance as a mechanism for the conservation of land and water resources and has most often been used in watersheds. PES typically connects upstream land users, often farmers, with downstream water users. Upstream land users may be paid to maintain current forest areas or plant additional trees, for not grazing on sloping lands, or any other land activities that could affect water quality and quantity for downstream cities, reservoirs, industries, or tourism areas (Binswanger-Mkhize et al. 2011).

Similarly, pasture management requires both access to water for the animals wherever they migrate to and access to pasture lands. The location of water sources influences pastoralists' choices of grazing areas, opens up new pasture areas, and thus improves animals' nutritional status. Consequently, water rights are the key to control and utilization of arid and semiarid areas. However, many pastoralists have formal rights neither over land nor over water (Binswanger-Mkhize et al. 2011).

The most promising avenue for addressing land and water scarcity is the reform of policies, rights, and institutions for SLWM to provide incentives to users for appropriate use. Reform efforts must start from the recognition that there are no one-size-fits-all solutions to policies, rights, and institutions, and no ideal solutions that apply everywhere, but that these have to be adapted to a country's or region's situation. However, some system of water and land rights should be at the start of any water and land management reform process.

ABBREVIATIONS

AGGDP	Agricultural gross domestic product
IPCC	Intergovernmental Panel on Climate Change
PES	Payment for Environmental Services
IWSR	Irrigation water supply reliability index
SLM	Sustainable land management
SLWM	Sustainable land and water management
UNFCCC	United Nations Framework Convention on Climate Change

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Section VI

Tools of Watershed Management

20 Watershed Management for Erosion and Sedimentation Control Case Study

Goodwin Creek, Panola County, MS

Seth M. Dabney, F. Doug Shields, Ronald L. Bingner, Roger A. Kuhnle, and James R. Rigby

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20.1 INTRODUCTION

Erosion and sedimentation are major global problems, with specific issues associated with loss of agricultural production, adverse impacts on infrastructure, and environmental degradation (Walling and Webb 1996). Erosion problems are particularly severe in hilly areas of the southeastern coastal plain of the United States, where annual watershed sediment yield is three to six times the national average for watersheds of similar size (Shields et al. 1995).

The Goodwin Creek watershed, located within this region of elevated sediment yield, provides an instructive case study of the dynamism of land use, where hydrologic, geomorphologic, and water quality characteristics can change over time; demonstrates how piecemeal application of accepted best management practices can have unanticipated long-term consequences; and illustrates the challenges inherent in attempting to assess the impact of conservation practices at the watershed scale (Bingner et al. 2007).

The Goodwin Creek watershed is located in north central Mississippi (89.8659 W, 34.2559 N). It is a tributary to Long Creek, and subsequently to the Yocona, Tallahatchie, Yazoo, and Mississippi

Rivers. At its confluence with Long Creek, Goodwin is a fourth-order stream. At the watershed outlet (Station #1), Goodwin has a drainage area of 21.3 km^2. It receives an average of about 1400 mm rainfall annually that is more or less evenly distributed over the months but often falls with higher intensity during the summer.

Goodwin Creek is located in the "bluff-hills" region, an area of thick loessal deposits located adjacent to and within about 35–70 km to the east of the Mississippi River alluvial plain ("The Delta"). Pleistocene loess overlies older coastal plains sand, clay, and gravel deposits (Grissinger et al. 1981; Grissinger and Murphey 1983). The loess thins to the east and is thickest (up to ~30 m) adjacent to the Delta. The Goodwin Creek watershed lies 15–25 km east of the bluff line (Delta/bluff-hills boundary), so prior to European settlement, the upland soils may have had loessal caps 2–3 m thick.

20.2 EARLY EUROPEAN SETTLEMENT

European settlers acquired control of the last 2,543,055 ha of Chickasaw Nation tribal lands, which included the Goodwin Creek watershed, in 1832 through terms of the Treaty of Pontotoc. Thereafter, rapid development involved land clearing and conversion to agriculture. The rolling or gently undulating upland loessal table lands were among the first lands cleared of their native oak/hickory forests because they were recognized to be productive, well drained, and easy to work.

One of the preeminent soil scientists of the nineteenth century, Eugene W. Hilgard, held faculty position at the University of Mississippi from 1855 through 1873. He also served as the state geologist of Mississippi. His writings describe and document the geology, soils, and early agricultural development of the region. According to Hilgard (1860, p. 293), one farmer characterized the loessal soil as "good enough as long as it will stay." However, when organic matter became depleted, productivity was lost because of low fertility and soil sealing that caused excessive runoff and erosion. Faced with depleted soils, the settlers moved on and cleared new lands, while "turning out" or fallowing older fields. Short periods of fallow improved fertility (Hilgard 1860, p. 206) but, Hilgard (1860, p. 295) warned, "It is highly important … to prevent the washes from penetrating the loam into the underlying sand or hardpan. Should the sand be loose, the moment the water reaches it, an undermining process will begin, which will cause the land to waste with greatly increased rapidity. Should it, on the contrary be an impervious hardpan, as is very frequently the case, the increased mass and velocity of the water will rapidly widen its channel, casting away the sides of the gully." The civil war greatly increased the amount of abandoned land, and the effects of uncontrolled gully growth during that period are recorded in valley sediment deposits of the region (Happ 1937).

According to the 1880 census, 34% of Panola County was classified as tilled lands, and of this, 45% was planted with cotton (*Gossypium* sp.) (Hilgard 1884). The cropland figure did not include the abandoned lands that grew at a rate and fashion alarming to Hilgard (1884, p. 238): "… unfortunately there has been a great deal of almost irretrievable damage done to these lands by allowing them to be washed and finally gullied by the rains, the water ultimately cutting into the underlying sand, and thereafter undermining the soil stratum and converting the hill lands into unavailable sand-hills, while the valleys also have been filled up with a mixture of sand and soil, the former usually predominating, rendering them almost as unavailable for cultivation as the hills … every year the evil increases in a geometrical ratio, and if unchecked must result in the serious and permanent injury to the agricultural interests of one of the fairest and naturally most favored portions of the state."

Nearly all the virgin timber in the region had been cut by 1910. The uncontrolled growth of upland gullies in the bluff-hills had proceeded. State geologist E.N. Lowe (1910) described the region as "the badlands of Mississippi." "The timber has been very largely removed, and much of the surface lies out in old fields." "The forests must be cleared and the lands must be cultivated for man's sustenance, and as long as he gives intelligent care to the soil washing need not result. It is only when he relinquishes it after clearing and cultivating it that it goes to destruction." Erosion problems were exacerbated by the common practice of the day of burning fallowed fields in the fall to improve visibility for hunting.

The period between 1910 and 1930 saw erosion of the upland areas at its worst. Most of the land had once been cropped and much was now abandoned and subjected to uncontrolled gully expansion. Forest cover was at a minimum. Steep-sided gullies grew until they approached the hill crests. Sandy sediments choked the stream channels, creating alluvial fans where they intersected floodplains. These sediment deposits diverted runoff flows onto the floodplains causing flooding from even minor storms of 2–3 cm (Happ 1937). Sandy splay deposits covered the more fertile natural soils and reduced productivity of the floodplain soils. Floodplain aggradation with "post-settlement alluvium" was frequently 2–3 m thick (Happ et al. 1940), and sometimes more than 8 m thick. The thickest deposits were located near the head of permanent stream flow, with 65% of the total deposition occurring within the upper 10 km of some Mississippi creek valleys (Happ 1975).

The original stream system had evolved in equilibrium with the runoff and sediment loads associated with intensive rainfall on mature forests growing on silty soils. The channels did not have the transport capacity to transport the sands washed from the upland gullies. In addition to creating flooding damage, sedimentation also eliminated navigation of the major rivers in the region. For example, state geologist Lowe (1922; as cited by Bennett (1939)) stated: "The Tallahatchie was formerly a navigable stream. Even as late as 1900 a small steamer drawing 4 ft of water plied the Tallahatchie from Batesville downstream. Now the stream is choked with sand bars, and can easily be waded at almost any place …" The severity of historical erosion within Goodwin Creek watershed was evidenced in the soil descriptions in the Panola County, Mississippi, soil survey (USDA-SCS 1963): only 2% of the land area was described as a nominal series, 11% was characterized as eroded, 40% as severely eroded, 26% as gullied, and 21% as floodplains.

20.3 DRAINAGE DISTRICTS

Watson et al. (1997) described the watershed development activities during the period from 1910 to 1939 as the "Drainage District Period." The first drainage law in Mississippi was enacted in 1886, and such laws became common in subsequent years. These laws empowered local districts to organize, issue bonds to be repaid with local taxes, and execute channel improvements. Most drainage works involved straightening the channels or digging laterals through the floodplains in order to increase conveyance and sediment transport capacity. The activity was related to cost–benefit calculations; the interest in drainage increased with cotton prices (Watson et al. 1997). The drainage district encompassing Goodwin Creek was called the Long Creek Drainage District No. 3 and was organized in 1922 (Olsen and Dumm 1941). This drainage district constructed about 10 km of ditches paid for with $19,000 worth of bonds. Construction of the "Smith Creek Lateral," which is the lowest 800 m of Goodwin Creek, was part of this activity. Gauging Station #1 of the Goodwin Creek Experimental Watershed is actually located within the constructed lateral at a point about 130 m south of the original channel's nearest approach (Figure 20.1).

Typically, several districts planned and constructed drainage works along a stream without coordination with each other. Often, channel activities of an upstream portion of a stream by one drainage district sent too much discharge and sediment to an unchannelized downstream reach of a different district (Watson et al. 1997). The equally ineffective approach of treating the channel system without first controlling upland management was documented by Happ (1937) for the case of the Wells Drainage District in adjacent Lafayette County that spent $30,000 to excavate bottom land drainage laterals in 1920 without treating the eroding upland gullies whose sand had clogged the natural stream channels. Benefits amounting to $54,000 were anticipated beyond the taxes totaling $55,000 to be collected to retire bonds by 1943. However, within 5 years of construction, sedimentation had caused the canals to cease to function properly.

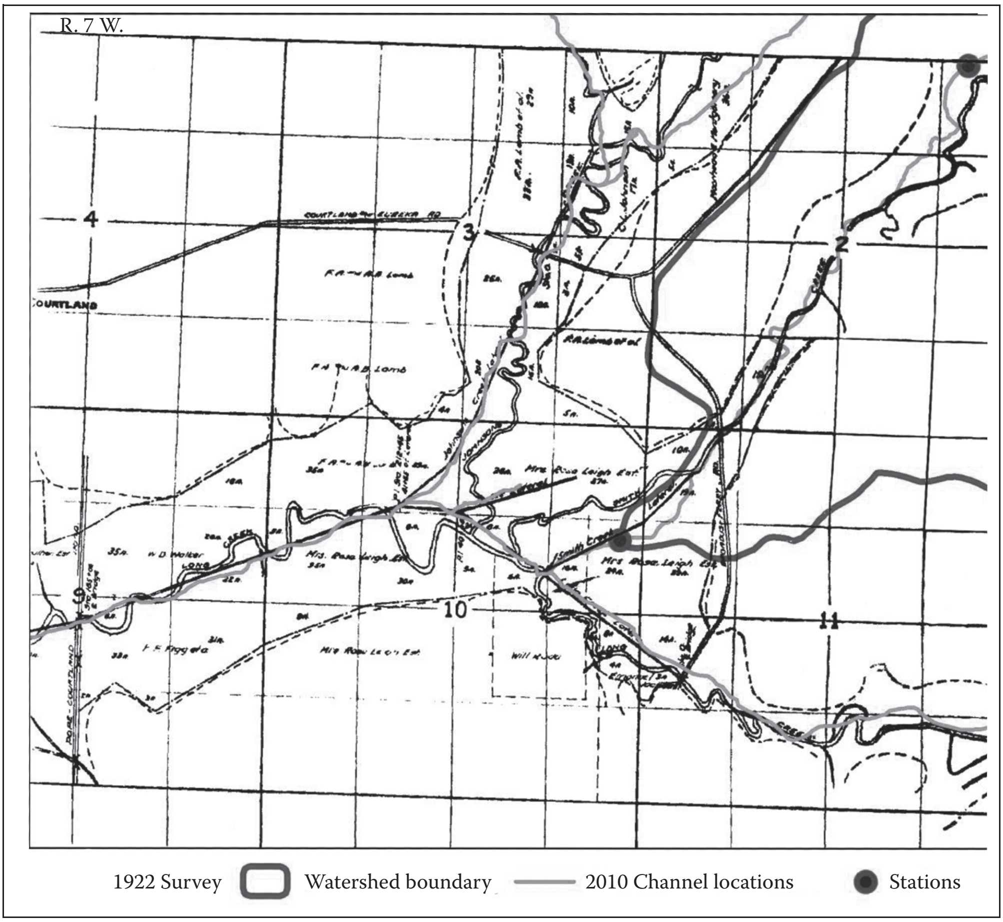

FIGURE 20.1 The Long Creek Drainage District No. 3 constructed 10 km (6.25 miles) of ditches and issued \$19,000 in bonds in 1922. The "Smith Creek Lateral" is now the lowest 800 m of Goodwin Creek. The gray line shows that the affected channels in 2010 remain considerably straighter, and therefore shorter and steeper, than before the drainage district project. Also shown are the locations of gauging stations #1 and #2 and the Goodwin Creek watershed boundary. Note that gauging station #1 is located on the constructed lateral at a point about 130 m south of the original channel.

20.4 FEDERAL INVOLVEMENT

20.4.1 Flood Control Dams

Following a devastating flood of the Mississippi River in 1927 (Barry 1997), the Federal Flood Control Act was passed in 1928 that established the U.S. Waterways Experiment Station at Vicksburg and empowered the Secretary of Agriculture to conduct research related to flood control such as reforestation. In 1936, legislation was passed mandating that floods on the Yazoo River were to be controlled with channel improvements, levee construction, and the construction of flood control reservoirs on the Coldwater, Tallahatchie, Yocona, and Yalobusha Rivers (Figure 20.2). One of these, the Enid Dam on the Yocona River, was constructed about 11 km upstream of the confluence with Long Creek with the Yocona. As discussed later, the closure of the dam in 1953 effectively lowered the base level of tributaries to the Yocona downstream of the dam.

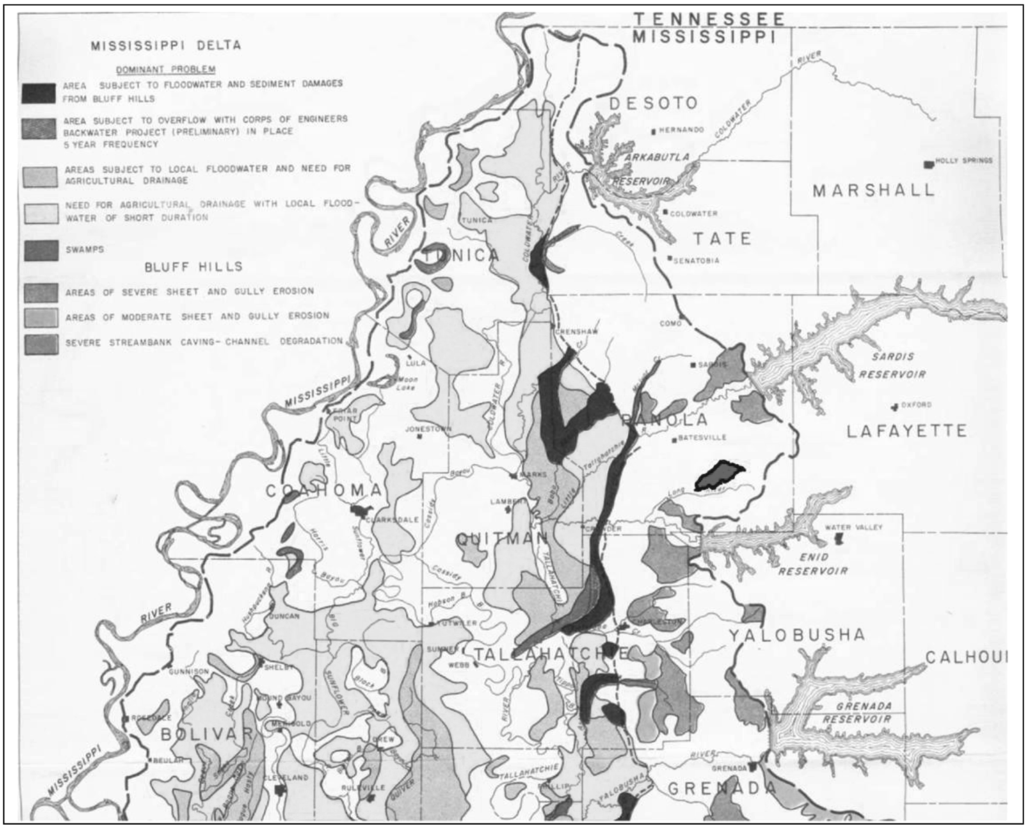
MISSISSIPPI DELTA
DOMINANT PROBLEM
AREA SUBJECT TO FLOODWATER AND SEDIMENT DAMAGES FROM BLUFF HILLS
AREA SUBJECT TO OVERFLOW WITH CORPS OF ENGINEERS BACKWATER PROJECT (PRELIMINARY) IN PLACE 5 YEAR FREQUENCY
AREAS SUBJECT TO LOCAL FLOODWATER AND NEED FOR AGRICULTURAL DRAINAGE
NEED FOR AGRICULTURAL DRAINAGE WITH LOCAL FLOODWATER OF SHORT DURATION
SWAMPS
BLUFF HILLS
AREAS OF SEVERE SHEET AND GULLY EROSION
AREAS OF MODERATE SHEET AND GULLY EROSION
SEVERE STREAMBANK CAVING- CHANNEL DEGRADATION
TENNESSEE
MISSISSIPPI
DESOTO
HERNANDO
COLDWATER
RIVER
ARKABUTLA RESERVOIR
HOLLY SPRINGS
MARSHALL
COLDWATER
TATE
SENATOBIA
TUNICA
TUNICA
RIVER
COMO
CRENSHAW
SARDIS
SARDIS RESERVOIR
OXFORD
PANOLA
BATESVILLE
LAFAYETTE
LULA
Moon Lake
MISSISSIPPI
FRIAR POINT
JONESTOWN
COAHOMA
CLARKSDALE
MARKS
LAMBERT
QUITMAN
WATER VALLEY
ENID RESERVOIR
RIVER
DUNCAN
YALOBUSHA
TALLAHATCHIE
SUMNER
WEBB
CALHOU
GUNNISON
SHELBY
ROSEDALE
BOLIVAR
GRENADA RESERVOIR
BEULAH
MISSISSIPPI
CLEVELAND
RULEVILLE
GRENADA
GRENADA

FIGURE 20.2 Following the construction of four major flood control reservoirs and the successful stabilization of upland areas by the YLT project, floodplains became an increasing source of sediment. Problems of streambank erosion were first recognized, as illustrated in this figure adapted from USDA-SCS (1961), in areas along the loess bluff line bordering the Mississippi Delta. In the following decades, headcut migration and streambank erosion became the dominant sources of sediment leaving upland watersheds in the region. Note the location of Goodwin Creek Experimental Watershed, which is a tributary to Long Creek and then to the Yocona River below the Enid Reservoir.

20.4.2 UPLAND EROSION CONTROL AND THE YLT PROJECT

Federal funds began to be expended to directly provide technical assistance to reduce the upland soil erosion on private lands following the creation of The Civilian Conservation Corps and the Soil Erosion Service in 1933, which was renamed the Soil Conservation Service (SCS) in 1935. In 1944, congress passed The Flood Control Act, PL 534, which established 11 watersheds throughout the United States, including the Yazoo and Little Tallahatchie River (YLT) watersheds in Mississippi, and authorized the Secretary of War, The Chief of the Corps of Engineers, and the Secretary of Agriculture to carry out works of improvement on them. The YLT Flood Prevention Project was officially launched in 1947 and lasted until 1985. On upland areas, USDA-SCS and USDA-FS worked together to reclaim gullies and return lands to constructive uses. Technology was developed and transferred and cost sharing was provided. Where land owners were interested, the worst gullied lands were afforested with loblolly pine (*Pinus taeda*) (Figure 20.3), which research showed provided the best and most rapid cover of pine straw mulch. Between 1948 and 1982, 339,000 ha of land was established in pine (Williston 1988; Duffy and Ursic 1991), while numerous farmland best management practices (BMPs) such as contour farming, terraces, grassed waterways, farm ponds, and grade control structures were applied on farmlands by SCS. The effectiveness of these upland

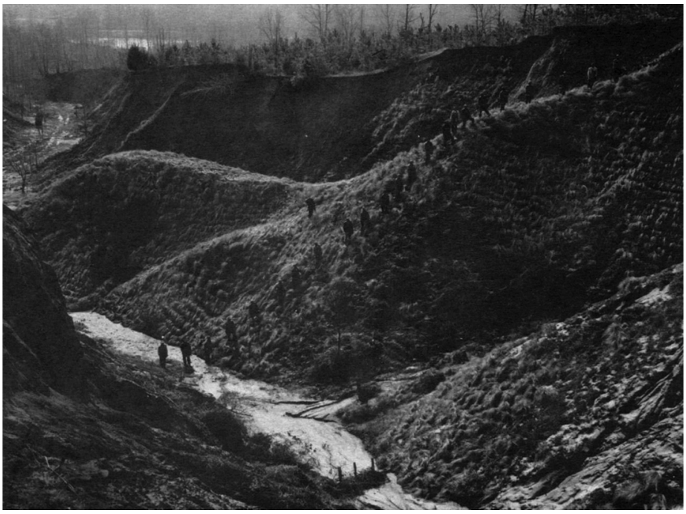

FIGURE 20.3 The YLT project reforested the most badly gullied land. In the case illustrated, strips of weeping lovegrass (*Eragrostis curvula*) were established to stabilize the actively eroding sandy gully sidewalls, and in the following winter, loblolly pine (*Pinus taeda*) seedlings were transplanted. Brush dams were constructed to stabilize thalweg areas before tree planting. (From Williston, H.L., The Yazoo–Little Tallahatchie Flood Prevention Project. A history of the Forest Service's role. U.S. Forest Service. Southern Forest Experiment Station. Forestry Report R8-FR 8, pp. 63, 1988; Duffy, P.D. and Ursic, S.J. *Land Use Policy*, 8, 196–205, 1991.)

conservation practices in increasing the amount of land covered with vegetation is evident in the time series of aerial photographs (1940, 1944, 1953, 1957, 1963, 1968, and 1976) of Goodwin Creek presented by Whitten and Patrick (1981).

20.4.3 DEC AND CEAP ERAS

As the amount of sediment generated from upland areas was reduced, a new problem of channel bank and bed erosion developed (Figure 20.2). Severe problems were first reported at the western boundary of the bluff-hills (USDA-SCS 1961). However, these problems soon propagated upstream and became widespread throughout the YLT watersheds, consistent with the conceptual models of incised channel evolution (e.g., Simon 1989). Happ (1975) concluded that in Yazoo River tributaries that had been dredged, or trenched by erosion headward from the dredged channels, channel and floodplain erosion exceeded the overbank deposition so that the valleys had become the sources rather than the repositories of sediment. Channel incision along the mainstem of Goodwin Creek produced steep, continually failing banks 4–5 m high and elevated sediment yield to ~1000 t/km^2 (Figure 20.4).

The growing recognition of economic losses associated with streambank erosion caused Congress to pass the River and Harbors Act of 1968 and the Streambank Erosion Control Demonstration Act of 1974, PL 93-251. Based on the 1974 legislation, the U.S. Army Corps of Engineers (COE) entered into a data collection and evaluation program with the USDA-ARS National Sedimentation Laboratory to test the concepts and designs of bed and bank stabilization techniques and to collect data needed for models evaluation over an indefinite period of time. The Goodwin Creek Experimental Watershed was ultimately selected and established in 1977. Two of the reasons why Goodwin Creek was selected included the following: (1) that it was less highly gullied than nearby watersheds and thus supported a wider range of land uses and (2) that it contained both straightened and natural stream reaches.

Prior to 1981, the COE constructed 14 supercritical grade control structures to stabilize the channel and serve as gauging stations operated by the Agricultural Research Service (ARS) (Figure 20.5).

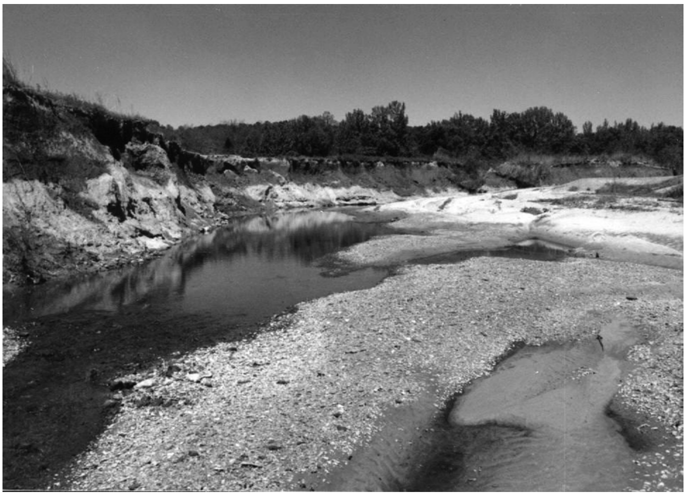

FIGURE 20.4 Concave bank of Katherine Leigh's bendway, Goodwin Creek, Mississippi, in 1986.

Land use, stream flow, water quality, and aquatic habitat data collection within the Goodwin Creek watershed became part of the ARS research program in 1980. Resulting data are available at http://www.ars.usda.gov/Main/docs.htm?docid=5120. In 1984, Congress authorized the Demonstration Erosion Control Project (DEC) to demonstrate the effectiveness of tools developed under PL 93-251 within the designated subwatersheds of the Yazoo River Basin. DEC funding for construction and monitoring continued until the late 1990s. Demonstration, evaluation, monitoring, and modeling research has continued in Goodwin Creek since 1980 and was intensified when Goodwin Creek was included as an ARS benchmark watershed in the cropland Conservation Effects Assessment Program (CEAP) in 2003. The goal of this assessment was to provide a better understanding of the role agricultural conservation practices and programs play in achieving the nation's environmental objectives—clean air and water, healthy soils, and functioning habitat for wildlife (http://www.ars.usda.gov/Research/docs.htm?docid=18645).

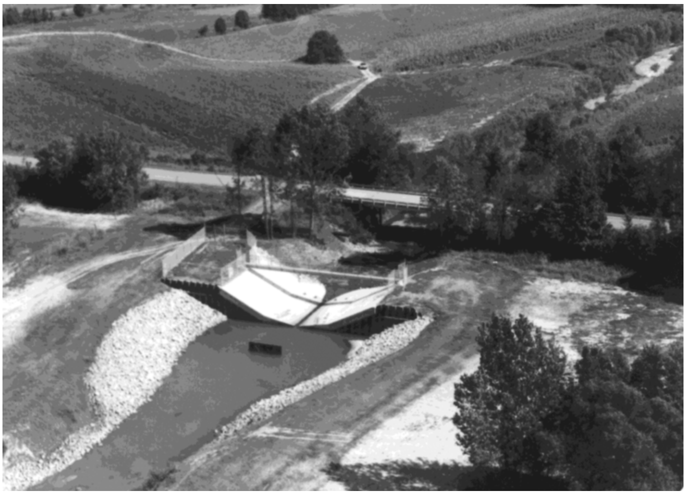

FIGURE 20.5 Goodwin Creek supercritical flow flume (Station #2) that serves as a grade control structure and flow and sediment discharge monitoring station.

20.4.4 CHANNEL EROSION CONTROL

Several attempts were made to stabilize the channel of Goodwin Creek and rehabilitate stream corridor habitats (Table 20.1). Construction of the aforementioned 14 supercritical flow flumes was completed prior to 1981 at a cost of $1.9 million (costs not adjusted for inflation; U.S. Army Corps of Engineers 1981). Flumes were designed to serve as grade control structures to prevent further channel incision and as monitoring stations to allow the measurement of water discharge and collection of sediment samples. The placement of these grade control structures arrested downcutting, and an average of 0.6 m of sediment deposition was reported for lower reaches in early 1989 (Neill and Johnson 1989). However, consistent with Stage IV/V of the incised channel evolution model (Simon 1989), lateral erosion and migration continued (Little et al. 1982; Figure 20.5). To address this erosion, stone stabilization structures were placed on the selected portions of the bank between gauging stations 1 and 2 in 1990–1991. Stabilization structures were longitudinal stone toe (6 ton/m) or short stone spurs ("groins"), which were generally placed on the outside of bends. These stabilization structures were effective in arresting lateral channel erosion, and stabilized banks were soon covered with deposited sediments and colonizing vegetation. However, bank failure following channel incision had widened the channel several fold, and the bank protection measures did not project far enough into the backflow channel to create scour pools that would benefit fish habitat. Fish habitat was generally degraded in Goodwin Creek by shallow depths, flashy hydrology, shifting substrate, and a lack of large wood and associated features (e.g., cover and scour pools) (Shields et al. 1994, 1998a). Reaches near the mouth had bank heights of 4–5 m, widths of 20–70 m, and thalweg sinuosity of only 1.12. Only 32% of the bank line was dominated by woody vegetation, and estimated canopy over the baseflow channel averaged 14%. Mean water depth was only 0.20 m, and large wood density was an order of magnitude smaller than for a nearby lightly impacted stream.

These deficiencies were partially addressed by extending 17 of the groins to create low weirs and by adding 11 spur-type extensions to the stone toe. In addition, 1729 dormant willow (*Salix nigra*) posts were planted adjacent to the modified stone structures. Few of the willows survived due to infertile soils (Grissinger and Bowie 1984; Pezeshki and Shields 2006) and competition from the exotic vine, *Pueraria lobata* (kudzu). The combined effects of grade control, groins, and spur dikes reduced bank and bed erosion and essentially stopped the thalweg migration. This is illustrated based on the analysis of aerial photographs from 1937, 1957, 1979, 1996, and 2006 at a location

TABLE 20.1
Channel Erosion Control and Habitat Restoration Projects, Goodwin Creek, Mississippi

Construction Date	Measures Emplaced	Length of Channel Treated (m)	Cost (Dollars Not Adjusted for Inflation)	Reference
1978–1980	14 grade control flumes	Systemic	$1,911,448	U.S. Army Corps of Engineers (1981)
1980	Toe protection and upper bank planting	160	$86,297	Bowie (1982, 1995), Shields et al. (1995)
1990–1991	Stone toe and groins	3000	$350,000 (est.)	n/a
1993	Stone weirs, spurs, and willow post plantings	1200	$50,000 (est.)	Shields et al. (1998a, 2007)
1993–1994	Woody and herbaceous plantings	200	n/a	Snider (1996)
2007	Toe protection, bendway weirs, upper bank plantings	100	$33,000	Simon et al. (2008)

defined as Katherine Leigh's bendway (Figure 20.6). Channel meandering was so destructive that some floodplain lands were taken out of production.

Physical aquatic habitat improvement was also almost immediate. Mean pool habitat increased from 32% to 78% of the water area. Biological response was more muted than the physical response, but fish collections in the 3 years following habitat rehabilitation produced fewer, larger fish than in the 2 prior years. Species composition shifted toward game and sportfish species that prefer pool habitats. The reach treated with spur-type extensions experienced a stronger biological response (Figure 20.7; Shields et al. 1998b). Ecological improvements persisted for at least 10 years (Shields et al. 2007).

More local efforts to control bank erosion using combinations of vegetation and structure and to accelerate the revegetation of the overwidened incised channel were attempted in 1980, 1995, and 2007. In 1980, the concave bank of a single bendway was treated with bank shaping; toe protection with stone, chain link, and pilings; and soil amendment and planting with native willow and six herbaceous species (Figure 20.8; Bowie 1982, 1995). The opposite convex bank was planted, but no toe protection was placed there. Thirteen years after construction, banks were stable and supported a lush mix of three of the planted species and several native invader species (Shields et al. 1995). In 1993–1994, test plots on a large point bar comprised of sand and gravel and selected portions of the opposite convex bank were planted with 7 herbaceous species and 17 woody species (Snider 1996). Plant materials included rooted seedlings, rhizomes, unrooted cuttings (stakes), and fascines (bundles of stems). Survival rates were generally low due to extremely harsh conditions imposed

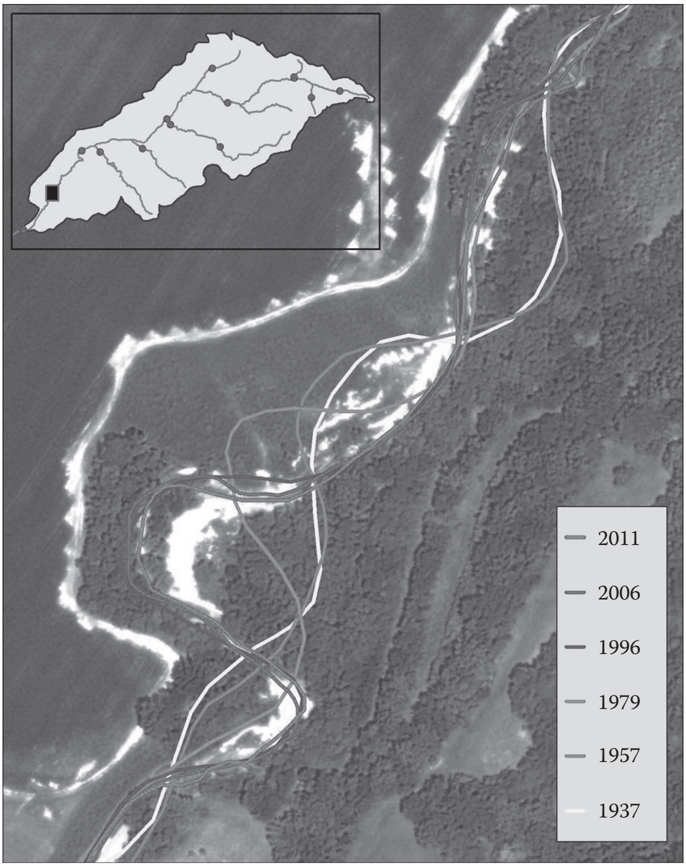

FIGURE 20.6 Migration of Goodwin Creek's Katherine Leigh bendway between Stations 1 and 2 from 1937 to 2011. Note that thalweg migration was greatly reduced after 1996.

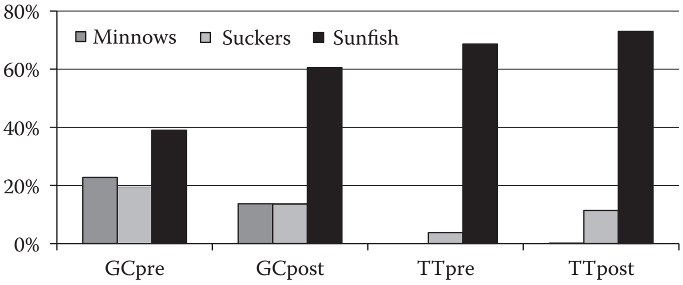

FIGURE 20.7 Impact of habitat rehabilitation on the distribution of fish biomass. GCpre = 1991–1992, prior to the construction of weirs, GCpost = 1993–1995, following weir construction. TTpre and TTpost are concurrent samples from a lightly degraded reference stream nearby. (After Shields, F.D., Jr, Knight, S.S., and Cooper, C.M., *Hydrobiologia*, 382, 63–86, 1998.)

by erosion, deposition, erosive flows, and drought. Shrubby willow species and giant reed (*Arundo donax*) performed well (Snider 1996), but the use of the latter is discouraged as it is an invasive exotic (Dudley 2000). In 2007, a 100-m steep, eroding convex bank was treated using stone toe, spur-type structures ("bendway weirs"), and upper bank plantings (Simon et al. 2008). The protection of an existing road necessitated a steeper bank slope (1V:1H) than stability criteria dictated for rapid drawdown conditions. The design involved geotechnical modeling of bank stability; the use of riparian vegetation to increase soil shear strength via root reinforcement to allow the use of the steep slope was a key aspect of the implemented design. As of this writing, the project has remained free from failure for 5 years.

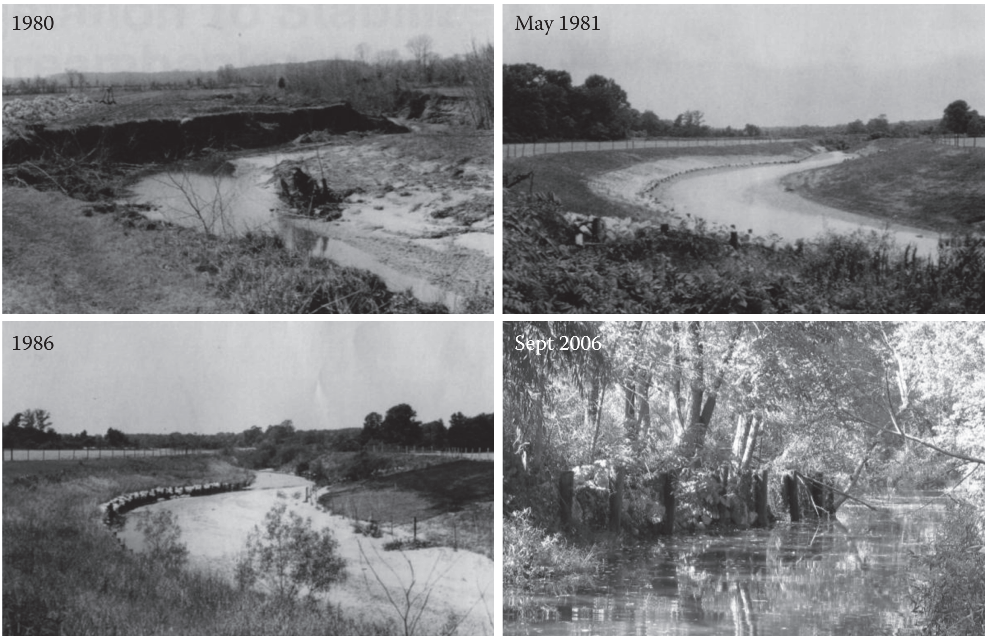

FIGURE 20.8 Vegetative streambank stabilization studies in Goodwin Creek proved successful, though expensive (From Bowie, A.J. *Transactions of the ASAE*, 25, 1601–1606, 1982; Bowie, A.J. Use of vegetation to stabilize eroding streambanks. U.S. Department of Agriculture, Conservation Research Report. 43, 24, 1995.)

and stable reaches have survived without maintenance for more than 20 years. Prior to construction, banks averaged 3.2 m in height and channel bottom widths ranged from 9 to 12 m. The bed gradient is 0.0049, and the catchment area above the study reach is approximately 14 km^2.

20.4.5 Land Use and Sediment Load Changes

Fine sediment (less than 0.062 mm in diameter) decreased between the years of 1982 and 1991 on Goodwin Creek (Figure 20.9; Kuhnle et al. 1996). The mean fine sediment concentration decreased from approximately 3000–1000 parts per million by weight (ppmw). The analysis of fine sediment concentration versus stream discharge showed a positive relationship between these variables, although the rating curve varied between rising and falling limbs of the hydrograph. During the period 1993 through 2003, researchers halted the sediment analysis, relying instead on the rating curve to calculate the sediment yield. Sediment sampling was reinitiated in 2003, and concentrations were found to be similar to those in 1993.

The decrease observed in the sediment concentration between the early 1980s and the mid-1990s corresponded to a reduction in the fraction of the land that was in cropland (Kuhnle et al. 2008; Figure 20.10), the previously described efforts at channel bank stabilization, and continued construction of ponds (Figure 20.11). Another structural practice that was commonly applied is "drop pipes," which allow surface runoff from fields to be conveyed to the level of incised streams without causing gully erosion (Figure 20.12). Peak runoff rates are also damped (Dabney et al. 2006). Sediment concentrations were higher during the third of the year from April through July, when average rainfall erosivity is higher and cropland is disturbed by tillage (Figure 20.9). Rating curve studies showed that stream fine sediment concentrations were higher at high flow rates, particularly during the rising limb of the hydrograph, so the observed lower concentrations and runoff rates may be due to either climatic or land management changes. Increased areas of grassland and forestland and more and larger ponds could reduce the peak runoff rates for equivalent rainfall inputs. Kuhnle et al. (2008) reported that the change in the percentage of cultivated land was coincident with a significant change in the runoff to rainfall relations for the April to July period.

20.4.6 Determination of Fine Sediment Sources

Sediment sources in the watershed have been determined using the naturally occurring radionuclides of ^{7}Be and ^{210}Pb$_{xs}$. These radionuclides are produced continuously in the atmosphere and are

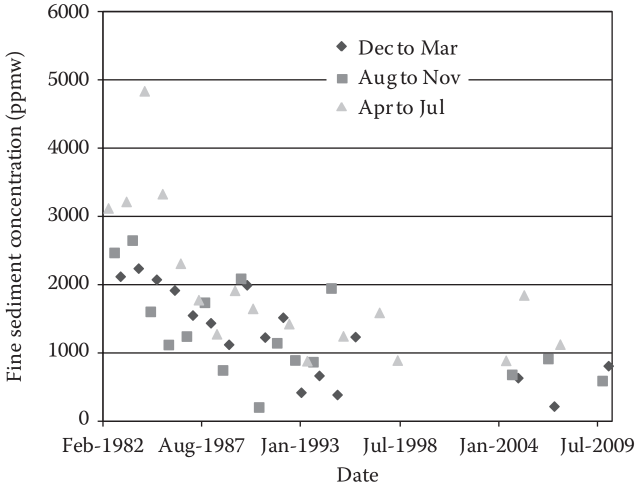

FIGURE 20.9 Coincident with the decreasing fraction of cropland in the watershed (Figure 20.10), the increase in the number of ponds (Figure 20.11), and the stabilization of streambank reaches, the flow-weighted average concentration of sediment <62 μm diameter declined. A significant seasonal effect—the higher spring/summer sediment corresponds to both tillage periods and periods—higher rainfall intensity are noted.

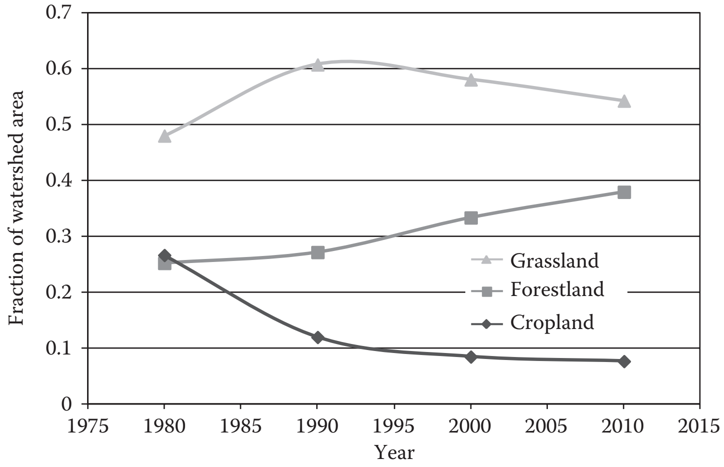

FIGURE 20.10 The fraction of the watershed area in cropland decreased substantially between 1980 and 1990, coinciding with conservation provisions of the 1985 Food Security Act and the creation of the Conservation Reserve Program. Subsequent to 1990, there has been a gradual increase in forested area and a gradual decline in cropland and grassland areas.

deposited on the land surface predominantly during rainfall events. The adsorption of radionuclides has been found to be restricted to the finer silt- and clay-sized particles, and thus source information is only available for these sizes using this technique. The unique signatures of the ratios of ^{7}Be to ^{210}Pb$_{xs}$ on surface soils and channel banks yielded an indicator that was compared to the radionuclide ratio of sediment transported in the channels. It was found that eroded surface soils make up the dominant portion of fine sediment in the channels during the first parts of runoff events, while later in a runoff event, sediment from bank sources predominates. Source information integrated over entire runoff events has revealed that 78% of fine sediment originated from channel sources on Goodwin Creek (Wilson et al. 2008). These findings are consistent with the estimates of erosion of

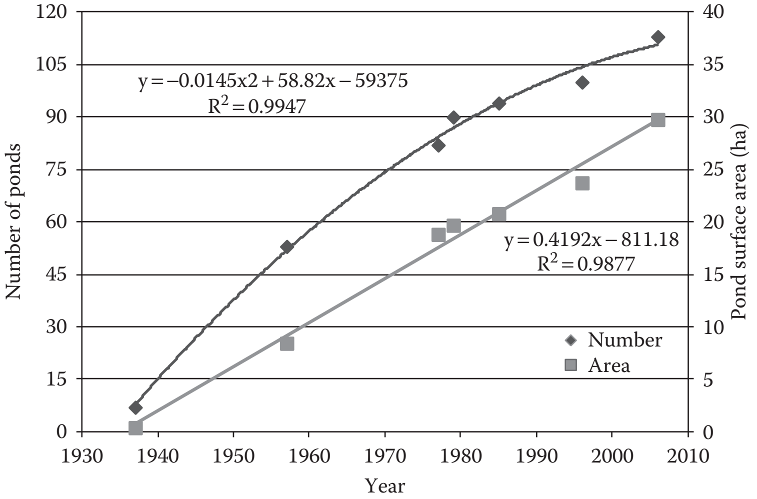

FIGURE 20.11 Based on the analysis of aerial photos, the number of ponds increases by about 2.3/year during the first 20 years, by 1.5/year during the next 30 years, and by about 0.9/year during the last 20 years. There has been a linear increase in the net pond surface area, which comprised 1.4% of the watershed area in 2010.

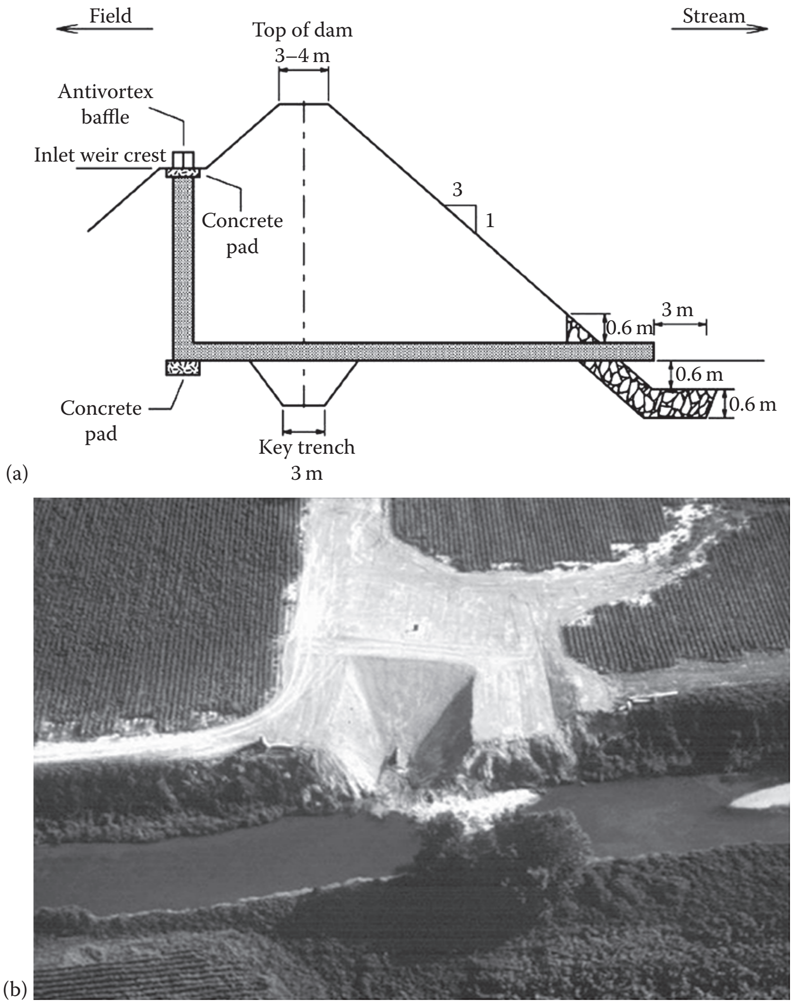

FIGURE 20.12 (a) A schematic of drop pipe structure including earthen embankment and (b) oblique air photo of a recently completed drop pipe viewed from the downstream (stream channel) side of the embankment.

channel beds and banks accounting for 75%–85% of the sediment transported through the channel system based on repetitive channel cross-section surveying (Grissinger et al. 1991) and watershed-scale simulation modeling (Kuhnle et al. 1996).

20.5 DISCUSSION AND IMPLICATIONS

While historically upland gully erosion was a serious sediment source in the region, at the current time, the erosion of incised channels is the predominant source of sediment transported from Goodwin Creek watershed. Efforts to stabilize the channel system during the last 30 years have produced mixed results (Watson et al. 1997). The main reason for the instability of the channel system is an imbalance between sediment transport capacity and sediment supply. Conservation practices applied to upland areas since the 1930s greatly reduced the upland sediment yield to channels. The reduction in runoff yield has been smaller, partly because of the persistence of topographical channel (gully) networks within the forested and pastured uplands.

Piecemeal drainage district efforts to alleviate flooding by straightening the stream system increased the stream gradients both directly (activities within the watershed) and indirectly by lowering the downstream base level (activities in the Delta). The construction of Enid Dam on the Yocona River also lowered the base level in the tributaries below the dam in two ways: (1) by retarding floods, the Enid Dam lowers the water levels in the lower Yocona during periods of intense runoff and (2) the discharge of sediment-free water from the dam resulted in scouring and lowering of the Yocona bed, thus steepening the gradient of tributaries (such as Long Creek) that join the Yocona downstream of the dam. Over time, the lower base level has propagated upstream in the form of headcuts.

The relatively sediment-free runoff flowing in steeper channels has unsatisfied sediment transport capacity, energy available to erode stream banks and beds. As channel erosion proceeds, the deeper and wider channels have the capacity to contain a greater percentage of peak flows, further concentrating the power of the flows within the channel system and reducing the connection of the streams to their floodplains. Practices to stabilize this type of inherently unstable channel system are difficult and expensive to implement (Table 20.1), and efficacy is uncertain (Shields 2008).

Land use has changed dramatically within Goodwin Creek watershed during the last 200 years. In 1800, the land was largely forested, and downstream rivers were reported to be deep and clear. By 1900, most of the land had been cleared, upland erosion was excessive, sediments were clogging channels, and streams were flooding bottomlands frequently. Today, cropland again represents less than 10% of the land area, and that mostly on the floodplains. Erosion of the channel beds and banks now accounts for 75%–85% of the sediment transported through the channel system.

In trying to assess the effect of field-scale Natural Resources Conservation Service (NRCS) conservation practices applied to cropland on water quality at the watershed scale, which is a main focus of CEAP, it is useful to reflect on the magnitude of upland BMPs that have already been applied in the Goodwin Creek watershed. The area has been part of at least one federal conservation demonstration program for most of the past 60 years. Ninety percent of what was once cropland has been converted to a conserving use (trees or grass cropland was 34% of Panola County in 1880; Hilgard 1884), with most other land either producing forages for draft animals or remaining idle; forests would soon be virtually eradicated. By contrast, during 2002, cropland had been reduced to 20% and reforested areas covered over 30% of the land (CTIC 2002). Although the percentage of cropland planted to cotton was about the same (45%) in 1880 and 2001, 95% of the cotton in Panola County in 2002 was planted no-till (CTIC 2002). Thus, although most of the land has received some conservation treatment, water quality in Goodwin Creek nevertheless remains impaired by sediment with stream banks and gullies being the predominant sources.

Over 50 years ago, King et al. (1956, p. 19) stated: "One outstanding need is some means of evaluating the benefits derived from land treatments … the comparative benefits derived from various individual treatments plus the overall cumulative effects of all treatments combined on a watershed basis." That statement was made relative to the joint USDA-FS and USDA-ARS research associated with the YLT program, but it could equally well apply to the objectives of CEAP today.

Goodwin Creek watershed is characterized with high rainfall erosivity, highly erodible soils, and (currently) relatively steep (0.004) and seriously incised channels. Total watershed sediment yield is among the highest in the nation (14.5 t/ha/year at station #1; Kuhnle et al. 2008). Suspended sediment concentrations regularly reach up to thousands of milligrams per liter during storm runoff events. High suspended sediment loadings have been shown to impact aquatic biota in streams and rivers in this region. The long historical record combined with 30 years of hydrological measurements provides a contrasting sequence of watershed management strategies during which uplands have been severely degraded and floodplains have acted first as sinks and now as sources of sediment. These experiences illustrate the possibilities, pitfalls, and limitations of using best management practices and watershed management to control erosion and sedimentation. Channelization as a management practice has been especially deleterious, creating a cascade of legacy impacts. Despite the almost irreversible environmental and economic damage caused by channel straightening, this management practice continues to be widely employed (Shields et al. 2011). The location and geography of Goodwin Creek watershed caused watershed degradation and adjustment processes to proceed more rapidly and to a greater extent than in other parts of the country, but the processes observed and lessons learned are believed to be broadly applicable.

20.6 SUMMARY AND CONCLUSION

The history of Goodwin Creek since European settlement can be read as a series of attempts to mitigate the unintended consequences of prior management. With the establishment of European control of lands drained by Goodwin Creek in 1832, the Goodwin Creek watershed underwent a phase of rapid land clearing and development resulting in the loss of virtually all forests in the watershed by 1910 in favor of pasture, cropland, and abandoned old fields. In the absence of forested area, the upland loessal soils suffered extreme erosion, thereby choking the streams with sediment. Because of the excess sediment supply to streams, a significant fraction of mobilized upland soils remained in the watershed forming new "post-settlement" deposits in channels and floodplains, in some cases contributing as much as 8 m of aggradation at the base of the upland slopes. This aggradation aggravated local flooding, which in turn motivated the establishment of institutional Drainage Districts to organize and manage engineering flood control projects. Drainage Districts set to the work of flood control primarily by straightening stream channels and constructing ditches, which increased the local stream gradients, draining the land more rapidly without addressing the excessive upland sediment supply, effectively only pushing the problem downstream within the larger, heavily agricultural, Yazoo River Basin. With the advent of federal involvement, regional flood control dams were constructed to manage flooding in the larger Yazoo River and Mississippi River Basins. The closure of Enid Dam in 1953 buffered the Yazoo Basin from flooding while also lowering the base level in the Goodwin watershed, adding further energy to an increasingly unstable system. Concurrent with the construction of Enid Dam, the Yazoo–Little Tallahatchie Flood Prevention Project initiated the reclamation of upland areas from widespread gullying, thereby reducing the sediment supply to channels in Goodwin Creek even as Enid Dam effectively steepened the channel gradients. With the supply of sediment from upland slopes greatly reduced by reclamation efforts, the banks and channels of Goodwin Creek became the primary source of sediment to dissipate the excess stream energy of the twice-steepened channels. While channel erosion control within the lower reaches of the watershed has been successful, even now large portions of the watershed are characterized by channel instabilities, which serve as the predominant source of degrading sediment.

From this sequence, at least four lessons can be gleaned. The first is the absolute necessity of considering the "downstream" effects of proposed management. In this sense, "downstream" may denote a spatial relationship within the watershed or even a temporal relationship as adjustment is a time-dependent process. In Goodwin Creek, the straightening of channel reaches "solved" the flooding problem locally by pushing the problem downstream. Similarly, the reclamation of the uplands from gullying reduced the sediment supply but did not consider the effect of a reduced sediment supply on the stability of stream channels.

The second lesson is an obvious corollary to the first. The management of erosion and sedimentation must always have in mind the dynamic balance of sediment and water. This point is highlighted in watersheds such as Goodwin Creek where few, if any, geologic constraints control erosion. As mentioned already, best management practices succeeded in stabilizing and reclaiming gullies on the uplands without equally decreasing the amount or energy of runoff in the streams. Kuhnle et al. (1996) summarized the effect of changing land use in the Goodwin Creek watershed in this way: "The major benefit in this watershed from a shift of a highly erodible land use to a nonerodible land use was not in the reduction of the amount of sediment from the upland areas but in the runoff leaving the upland areas and then its subsequent effect to reduce channel erosion and sediment transport." Thus, while erosion and sedimentation are the more visible vestiges of a problem, runoff remains the underlying supply of energy for channel erosion.

A third potential lesson from Goodwin Creek's history concerns the impact of institutions on watersheds. Institutional involvement in Goodwin Creek occurred primarily through the work of the Drainage Districts and subsequently by the flood control efforts of the federal government. The channelization of Goodwin Creek under the direction of the Drainage District reduced local flooding while pushing sedimentation and flooding problems downstream in the watershed. Clearly, local institutions have nonlocal effects. At the regional scale, the construction of flood control reservoirs produced downstream effects (base-level lowering), which then propagated upstream through the tributary watersheds such as Goodwin Creek. Thus, large-scale institutions and projects will directly affect the stability of smaller-scale systems within the region and may create upstream-propagating disturbances such that no portion of a large watershed is fully decoupled from nonlocal practices. An important lesson to take away, therefore, is that increases in the scale of management are not necessarily equivalent to increasing the necessary coordination of management within a basin or watershed.

Lastly, Goodwin Creek demonstrates that the effects of past management decisions cannot simply be undone. While reforestation of the watershed led to the stabilization of the uplands, it also destabilized the channels themselves because of the very flood control efforts aimed at mitigating the unintended effects of upland erosion. Furthermore, the behavior of reforested land can be expected to differ substantially from the same land when it was covered by virgin forests due to the degradation of surface soils and the presence of remnant gully channels that increase connectedness and reduce times of concentration. In a tightly coupled system, if management is always only aimed at mitigation, we risk always chasing our own unintended consequences in circles through the logic of watershed adjustment. This irreversible aspect of watershed adjustment demands management of the system based on its present state and functioning rather than on how it functioned when the previous management practices were put in place and led to unintended consequences (which have almost certainly changed the state of the system).

In sum, the message presented by the history of management efforts in Goodwin Creek is the necessity of *coordinated* watershed management. The many efforts in Goodwin Creek demonstrate the development of technical expertise and effectiveness in addressing local issues of upland erosion and channel stability. The more general challenge is to coordinate this expertise throughout the physically coupled system so that one fix does not make another problem worse. Evidence has been presented that Goodwin Creek channels have not yet stabilized to current channel gradients, runoff rates, and sediment loads. The continued construction of private ponds within the watershed may be an effective means of reducing runoff rates in the near term. However, only time, perhaps a century or more, will allow the soil depths and infiltration capacities of degraded areas now covered by forestlands to gradually improve, thereby reducing hydrograph peaks and increasing base flow, and for the stream channel system to gradually evolve to a stable lower-gradient state.

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Section VII

Research and Development Priorities

21 Toward Enhancing Storage of Soil Water and Agronomic Productivity

Rattan Lal

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21.1 INTRODUCTION

The renewable freshwater resources (RFWR) are limited (Table 21.1) and are determined by the global hydrological cycle (Oki and Kanae 2006). With the increase in population from 7 billion in 2011 to 9.2 billion in 2050, there will be a greater competition for water use by agriculture than for industrial and urban uses. There will also be additional water use for improving the environment (i.e., C sequestration) for nature conservancy (i.e., restoration of wetlands, and wildlife habitat) and for recreational purposes. Limiting and decreasing water resources must be judiciously managed for both people and nature (Postel and Richter 2003). The availability of freshwater resources will also be confounded by the projected climate change. The hydrological cycle is likely to be intensified by climate warming (Huntington 2010), with possible adverse effects on the availability of fresh water for competing uses. Thus, sustainable management of water resources, using the strategies of integrated water management (IWM) (Bouwer 2002) and ecohydrological approach (Falkenmark and Rockström 2005) among others, is essential to meeting the growing demands. While agriculture currently uses about 70% of the total water withdrawal (Molden 2007), decline in its share of the scarce resource is inevitable because of numerous competing but essential uses. Estimates of calories produced per cubic meter of water range from 1000 to 7000 for corn, 1260 to 3360 for legumes, 500 to 2000 for rice, and 60 to 210 for beef (Molden et al. 2007). Therefore, understanding the hydrological processes in agricultural and related ecosystems is essential to improving the use efficiency by decreasing the losses. The themes of Chapters 1–20 presented in this volume address the scientific processes, technological options, and policy interventions to enhance effective water use. This chapter is focused on addressing the research and development priorities in improving soil water storage for enhancing and sustaining agronomic productivity with the goal to advance the global food security, while improving the environment.

TABLE 21.1
Global Reserves of Water

Reservoir	Storage (10^3 km^3)
Sea	1,338,000
Glaciers and snow	24,064
Permafrost	300
Lakes	175
Wetlands	17
Soils	17
Water vapor	13
• Over ocean	(10)
• Over land	(3)
River	2
Biological	1
Total	*24,589*

Source: Recalculated from Oki, T. and Kanae, S., *Science*, 313, 1068–1072, 2006.

21.2 FACTORS AFFECTING SOIL WATER STORAGE

There is a large water footprint for agricultural production (Khan and Hanjra 2009), and its magnitude differs widely among ecoregions, land uses, and soil types. Soil water, its storage, and its efficient use are critical to reducing the footprint of agriculture. Global soil water storage is estimated

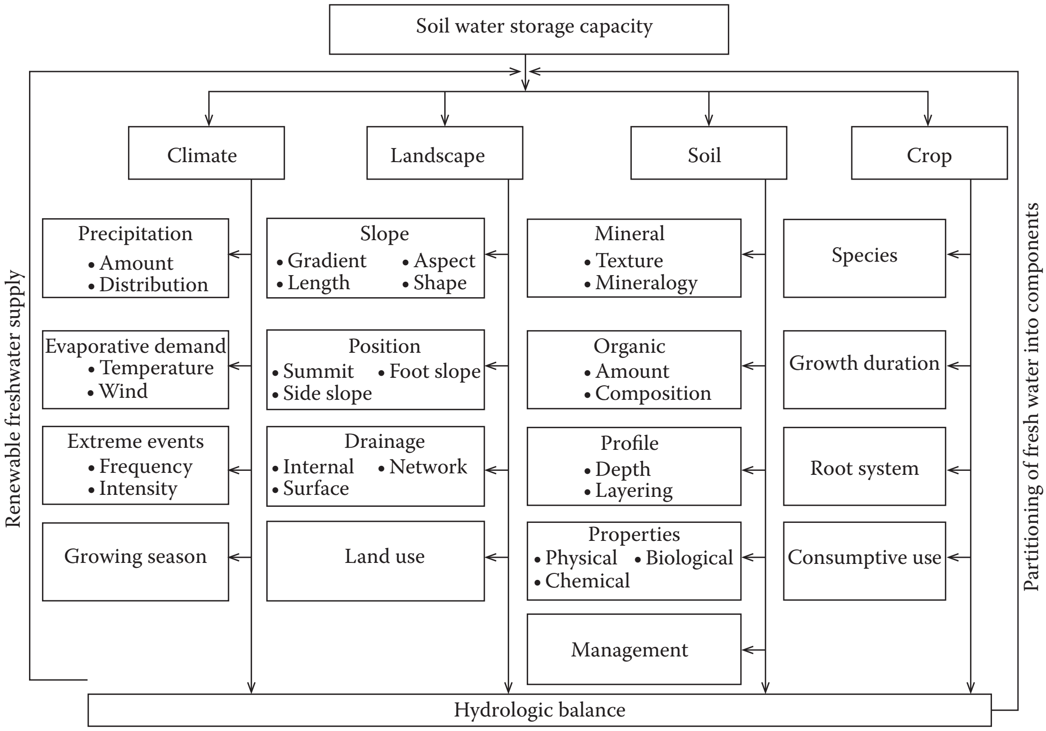
Soil water storage capacity
Climate
Landscape
Soil
Crop
Precipitation
• Amount
• Distribution
Evaporative demand
• Temperature
• Wind
Extreme events
• Frequency
• Intensity
Growing season
Slope
• Gradient
• Aspect
• Length
• Shape
Position
• Summit
• Foot slope
• Side slope
Drainage
• Internal
• Network
• Surface
Land use
Mineral
• Texture
• Mineralogy
Organic
• Amount
• Composition
Profile
• Depth
• Layering
Properties
• Physical
• Biological
• Chemical
Management
Species
Growth duration
Root system
Consumptive use
Renewable freshwater supply
Partitioning of fresh water into components
Hydrologic balance

FIGURE 21.1 Factors affecting soil water storage capacity.

TABLE 21.2
Factors Affecting Capacity and Use Efficiency of Soil Water

Soil Properties	Soil Management	Crop Management	Water Management
Texture	Tillage methods, nutrients	Root system	Drainage
Structure	Mulching, conservation agriculture, cover crops, biomass	Crop rotations, farming system	Quality of irrigation water
Soil organic matter	Compost, manure, INM, mulching, conservation tillage	Complex crop rotations, agroforestry, agropastoral systems	Water conservation, irrigation, wastewater use
Compaction	Guided traffic, chiseling, soil fauna	Deep-rooted crops	Runoff control, infiltration management
Low water retention	Mulching (plastic, gravel, crop residues), conservation tillage	Crops and cropping systems, time of sowing	Water harvesting microirrigation, wastewater use
Low soil fertility	Integrated nutrient management, balanced nutrient application	Legume-based rotations, grazing management	Soil water conservation, irrigation with treated gray water
High salt concentration	Conservation tillage, mulching, balanced nutrient application, composting	Tolerant crop species, rotation, use of saltbush, halophytes	Microirrigation using marginal and saline water for irrigation

at 17×10^3 km^3 (Oki and Kanae 2006). Among three types of drought (i.e., meteorological, hydrological, and agronomic), agronomic drought depends on the soil's available water capacity (AWC), and meteorological drought is caused by climatic factors. While building resilience in drought-prone agriculture is important (Falkenmark and Rockström 2008), it can be realized through increasing soil water storage and enhancing its water productivity (WP) and use efficiency. The soil water storage of 17×10^3 km^3 (Table 21.1) is the source of water for all terrestrial life. It is augmented by storage in glaciers/snow, lakes, permafrost, wetlands, rivers, and atmospheric water vapor. Yet, it is crucial to all life. There is a wide range of factors that affect capacity and use efficiency of soil water (Figure 21.1 and Table 21.2). Principal among soil factors are profile/solum depth, texture, mineralogy, structure, soil organic matter (SOM) content, AWC, salt concentration, and nutrient reserves and availability. While the solum thickness and the effective rooting depth are determined by natural forces, other factors (i.e., soil structure, fertility, compaction, salt concentration, and SOM content) can be managed to enhance AWC and its use efficiency. There are several soil, crop, and water management options (Table 21.2). Important among these are those that enhance soil and water conservation (i.e., conservation tillage, mulch farming, contour hedges), soil fertility, and nutrient reserves (i.e., integrated nutrient management [INM] involving manuring, composting, biological N fixation, mycorrhizae), and supplemental irrigation (see Section 21.4). The goal is to restore degraded soils and desertified ecosystems to improve water infiltration and AWC. Similar to soils, crops can be managed to enhance plant water uptake. The choice of an appropriate crop, along with cropping sequence and crop combinations, is important to moderate growth duration and consumptive water use. The latter is also influenced by the nature of root systems and soil properties. Factors (Figure 21.1) and management options (Table 21.2) can be managed to influence the hydrologic balance at soilscape, landscape, and watershed scale to improve water availability for agroecosystems. Management also depends on economic and social factors, which comprise the human dimensions of natural resource management.

21.3 CLIMATE CHANGE AND SOIL WATER REGIME

While the anthropogenic increase in the atmospheric concentration of greenhouse gases (i.e., CO_2, CH_4, and N_2O) is undisputable, there is much uncertainty about the magnitude of changes in climate, soil properties, and hydrological parameters. It is probable that the projected climate change and increase in temperature and evaporation may adversely affect the supply of RFWR through alterations in a wide range of ecosystem attributes and processes (Figure 21.2). Notable among these are alterations in microclimatic and mesoclimatic factors (i.e., precipitation amount and distribution, evaporation, run-on/runoff and groundwater recharge, and the components of hydrologic balance). There are widespread reports of decrease in rainfall throughout the Mediterranean region, Sahel, southern Africa, the Aral Sea Basin, and Australia, since the early twentieth century (Ragab and Prudhomme 2002). A decline in precipitation, in conjunction with an increase in temperature and evaporation, would severely jeopardize the availability of freshwater resources. The adverse effects on soil water storage will be exacerbated by a decline in soil hydraulic properties and processes (i.e., moisture retention characteristics, infiltration capacity, and rooting depth) and changes in land use and plant species. It is widely argued that climate change may intensify the hydrologic cycle (Huntington 2010) and increase evaporation, evapotranspiration, atmospheric water pool, and (in some cases) total precipitation. However, global trends in soil water storage are uncertain because of the effects of other confounding factors (Figure 21.2). In addition to soil factors, increase in frequency and intensity/duration of extreme events (i.e., drought, runoff, erosion, and floods) may also affect the soil water storage (Huntington 2010). These factors may adversely affect the water resources in the Near East (region covering 29 countries and an area of 18.9×10^6 km^2, from Mauritania/Morocco in the west to Pakistan in the east), which is about 14% of the world's total area (Ragab and Prudhomme 2002). Although the rainfall over the Sahara may increase, it is of little agronomic consequence. The average annual precipitation may also decrease in the Thar Desert (India, Pakistan, and Afghanistan).

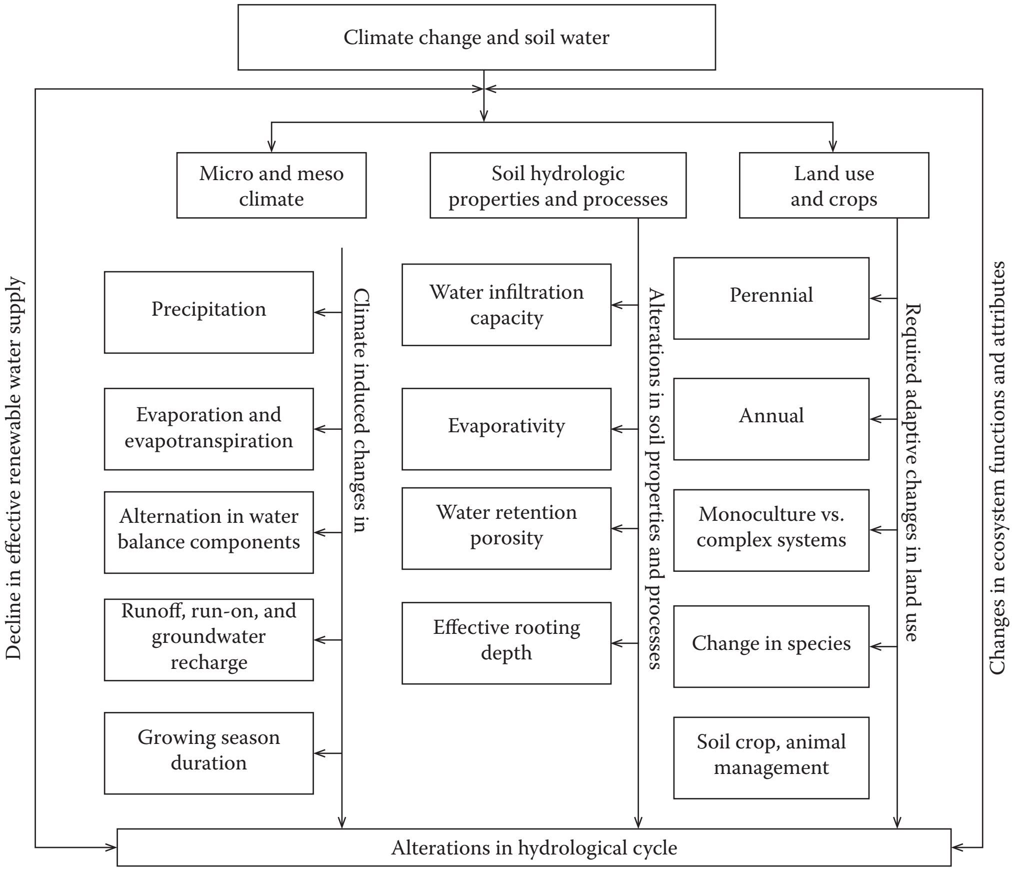
Climate change and soil water
Micro and meso climate
Soil hydrologic properties and processes
Land use and crops
Climate induced changes in
Alterations in soil properties and processes
Required adaptive changes in land use
Decline in effective renewable water supply
Changes in ecosystem functions and attributes
Precipitation
Evaporation and evapotranspiration
Alternation in water balance components
Runoff, run-on, and groundwater recharge
Growing season duration
Water infiltration capacity
Evaporativity
Water retention porosity
Effective rooting depth
Perennial
Annual
Monoculture vs. complex systems
Change in species
Soil crop, animal management
Alterations in hydrological cycle

FIGURE 21.2 Potential effects of projected climate change on soil water storage and availability.

21.4 AGRONOMIC PRODUCTIVITY

Implications of climate change on soil water storage and agronomic productivity (Rosenzweig and Hillel 1998) are not clearly understood. A major uncertainty is due to the confounding interaction with CO_2 enrichment or the CO_2 fertilization effect (Polley 2002), which itself depends on the availability of soil moisture and plant nutrients. Soil- and site-specific research is needed for the measurement and modeling of the agronomic effects. The role of soil/pedospheric processes on climate-induced changes in agronomic productivity cannot be overemphasized. For example, changes in SOM content, because of increase in temperature-related decomposition, on risks of accelerated soil erosion, can affect soil quality and use efficiency of water and nutrients. Decline in SOM content to below the threshold level may have severe agronomic, ecologic, and economic implications. While increasing the terrestrial C pool (soil and biota) is considered a win-win option, there are notable trade-offs between C and water. Afforestation and establishing plantations, as well as options for increasing the C pool of degraded and desertified ecosystems, may decrease the stream flow and also exacerbate risks of soil salinization and acidification (Jackson et al. 2005).

The agronomic data, based on well-designed field experiments to assess the impact of climate change on crop/tree/animal performance, are scanty. The scarcity of data is specifically imminent in climate-induced changes in soil properties and plant AWC. The latter is affected by a range of interacting soil properties and processes (Figure 21.3). Rather than a sole determinant, effects of soil properties and processes are highly interactive both within and outside the pedosphere. While assessment of the changes within the pedosphere is a challenge in itself, it is even more difficult for those caused by interaction with the environment (Figure 21.4). Specific interactive processes that are a high researchable priority include the CO_2 fertilization effect (in relation to water and nutrients supply), biological weathering by bioturbation processes, transport of dissolved and suspended materials within and

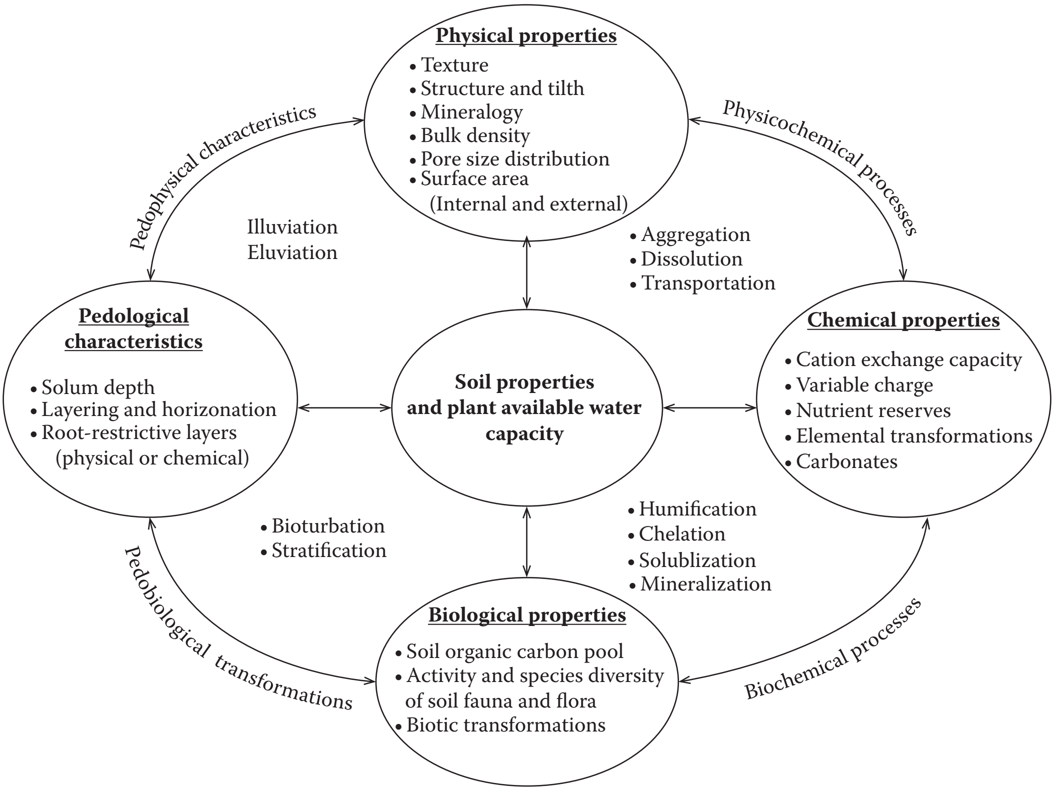
Physical properties
• Texture
• Structure and tilth
• Mineralogy
• Bulk density
• Pore size distribution
• Surface area (Internal and external)
Pedophysical characteristics
Physicochemical processes
Illuviation
Eluviation
• Aggregation
• Dissolution
• Transportation
Pedological characteristics
• Solum depth
• Layering and horizonation
• Root-restrictive layers (physical or chemical)
Soil properties and plant available water capacity
Chemical properties
• Cation exchange capacity
• Variable charge
• Nutrient reserves
• Elemental transformations
• Carbonates
• Bioturbation
• Stratification
• Humification
• Chelation
• Solublization
• Mineralization
Pedobiological transformations
Biochemical processes
Biological properties
• Soil organic carbon pool
• Activity and species diversity of soil fauna and flora
• Biotic transformations

FIGURE 21.3 Potential effects of climate change on soil properties and plant available water capacity.

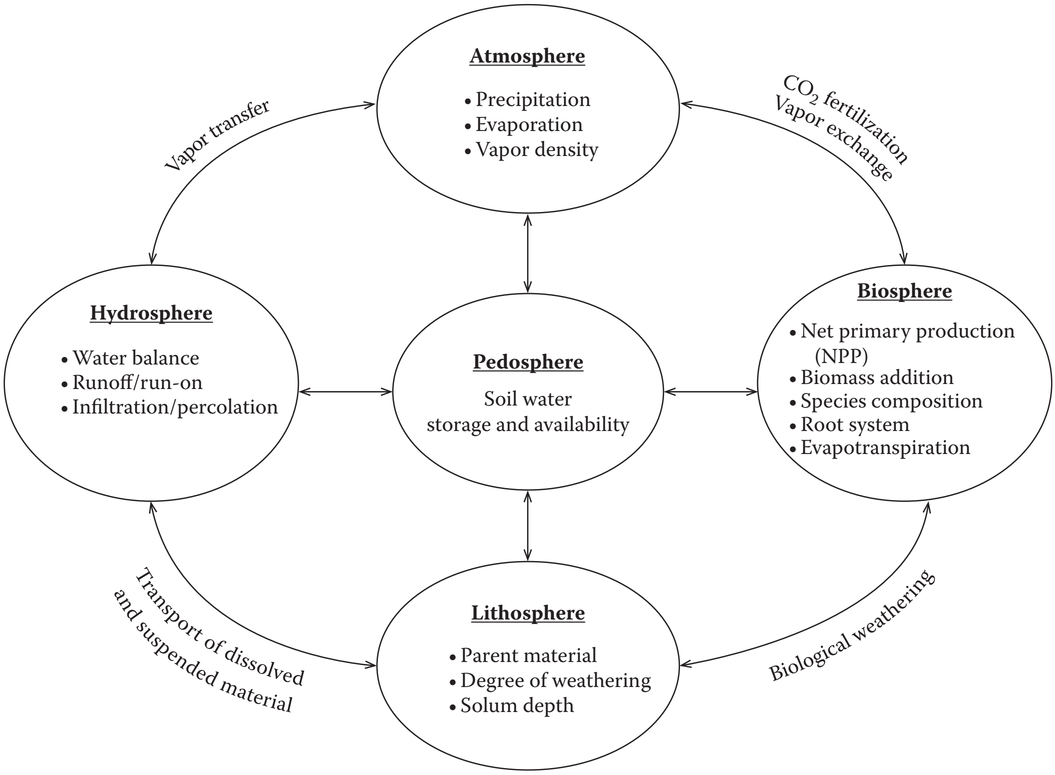
Atmosphere
• Precipitation
• Evaporation
• Vapor density
Vapor transfer
CO2 fertilization
Vapor exchange
Hydrosphere
• Water balance
• Runoff/run-on
• Infiltration/percolation
Pedosphere
Soil water
storage and availability
Biosphere
• Net primary production (NPP)
• Biomass addition
• Species composition
• Root system
• Evapotranspiration
Transport of dissolved
and suspended material
Biological weathering
Lithosphere
• Parent material
• Degree of weathering
• Solum depth

FIGURE 21.4 Interactive effects of pedosphere with the environment in relation to soil water storage and availability.

outside of the pedosphere, and vapor exchange between the atmosphere on one hand and biosphere and hydrosphere on the other (Figure 21.4). Soil- and ecoregion-specific data are also needed concerning the interaction between the pedosphere and the atmosphere for gaseous exchange (CO_2, CH_4, and N_2O), biosphere for nutrient/elemental cycling (N, P, and S), lithosphere for material transport, and hydrosphere for leaching (illuviation and eluviation) and erosion (Figure 21.4).

It is the complexities outlined in Figures 21.3 and 21.4 that create numerous uncertainties with regard to the impact of climate change on agronomic productivity. The effects on agronomic productivity, discussed by Rosenzweig and Hillel (1998) and Ragab and Prudhomme (2002), may differ among temperate and tropical regions (Table 21.3). The adverse effects on agronomic production,

TABLE 21.3
Potential Effects of Climate Change on Agronomic Productivity

Parameter	Temperate/Boreal	Tropics/Subtropics
Growing season duration	Increase	Decrease
CO_2 fertilization effect	Positive	Negative on grain yield (positive on biomass)
Pest incidence	Increase	Increase
Water deficit/drought	Uncertain	Exacerbate
Net radiation	Uncertain	Decrease
Soil water storage	Uncertain	Decrease
Agronomic yield	Increase	Decrease

more severe in the tropics than in temperate climate, may aggravate the food insecurity, which is already a serious problem in the tropics.

21.5 ENHANCING USE EFFICIENCY AND PRODUCTIVITY IN RAINFED AND IRRIGATED AGRICULTURE

Irrigated agriculture, with an arable land area of <20%, produces 40% of the world's agronomic output comprising cereals, legumes, roots, and tubers. Therefore, sustainable management of irrigated agriculture is a high priority, especially in consideration of the fact that less fresh water may be available for maintaining the existing area and bringing new area under irrigation. The proposed 30% increase in irrigated area by 2030 (Kijne 2001) can only be implemented by diverting surface (blue water) and municipal (gray water) water to soil water (green water). With rapidly increasing and competing demands for blue water, there will be an increasing use of brackish water (refer to Chapter 11) and municipal wastewater (Jueschke et al. 2008). However, the use of municipal water for agriculture would necessitate pretreatment to minimize health risks (WHO 2006). Such facilities for treating wastewater are not available in developing countries of the tropics and subtropics, where the risks of health hazards are already serious.

The WP under traditional flood irrigation is low. Considerable savings in water can be realized by adopting modern irrigation systems including drip subirrigation, other microirrigation techniques, and partial root-drying strategies (Lindbolm and Nordell 2006). Subsurface irrigation by condensation of humid air (condensation irrigation or CI) is also an option, especially for hot/arid regions. The CI is a system that combines a solar desalination system with subirrigation (Lindbolm and Nordell 2006). Solar stills are used to evaporate brackish water, and the humid air is then carried into a network of underground pipes to condense it into liquid water at cooler temperature. The condensed water and humid air irrigates the root zone of a crop. As much as 3 kg (3L) of H_2O can be condensed per meter of the cooling pipe (Lindbolm and Nordell 2006).

Rice paddy, grown under flooded conditions in a puddled soil, is a water-intensive production system. The rice–wheat system practiced in the Indo-Gangetic Plains of South Asia (Chapter 6) has severely depleted the groundwater reserves (Rodell et al. 2009; Kerr 2009). Severe depletion of groundwater is also reported in China (Chapter 12), the Middle East (Chapter 7), and the U.S. Great Plains (Chapters 4 and 5). With adequate weed control and seeding equipment, specific varieties of aerobic rice can be grown under upland conditions, similar to the cultivation of wheat. There are other water management options for rice, especially suited to conditions of water scarcity (Bouman et al. 2007).

Water harvesting and recycling for supplemental irrigation have been practiced for millennia, especially in arid regions of Asia. Water harvesting, used in conjunction with innovated irrigation technologies discussed earlier, is important in enhancing WP. A runoff-based agroforestry system can also improve water-use efficiency (WUE) in arid climates. The strategy is to combine deep-rooted perennials with shallow-rooted annuals (Droppelman et al. 2000).

Using plant hydraulic lift by perennials to benefit annuals grown in arid climates is another option. Roots of some desert trees (i.e., shepherd's tree or *Boscia albitrunca*) can extract water from 68 m below the surface (Canadell et al. 1996), because plant roots can carry water from deep soil layers (Clothier and Green 1997). Termites and other soil fauna (harvester ants) also carry water from subsoil to their nests on the surface. The process by which water is transported upward through root systems from the subsoil (moist layer) to the surface soil (dry layer) is termed hydraulic lift (Liste and White 2008). Water transport by the hydraulic lift of perennials with a deep root system can be used to cultivate annuals grown in association (as an agroforestry system) to produce some agronomic yields even under harsh climates where complete crop failure is inevitable (Espeleta et al. 2004; Oliveira et al. 2005). The process can be used in ecoregions that experience frequent surface droughts (agronomic drought) but have water reserves deep in the subsoil (i.e., Mediterranean climates, arid and cool temperate regions, seasonally dry tropical and subtropical environments, and the Mojave Desert). The magnitude and pattern of hydraulic lift may differ among perennials and companion annuals and also among soil types and the depth of the moist layer.

21.6 RESEARCH AND DEVELOPMENT PRIORITIES

While the general principles of soil, water, and crop management may be known, site-specific research is essential to identify practices that can adapt to changing climate. Some researchable priorities (Table 21.4) have been discussed in the previous sections. The strategy is to validate and fine-tune the practices for sustainable management of soil (i.e., conservation tillage, mulch farming, nutrient requirement, AWC, and SOM management), crop (i.e., choice of species and varieties; time, configuration, and methods of sowing; consumptive water use; CO_2 fertilization effect; hydraulic lift; and growing season duration), and microclimate (i.e., temperature, precipitation, extreme event, hydraulic balance, and radiation budget). Adaptation is possible when basic information on soil, crops, and microclimate and mesoclimate is known. This information is needed at soilscape, landscape, and watershed (agricultural watersheds and river basin) scales.

Adoption of recommended management practices (RMPs) for saving water and enhancing WP can be promoted through payments to land managers for ecosystem services. Similar to soil C credits, green water credits is a mechanism for payments to land managers for adopting water-saving practices (Dent 2006). Incentivizing the land managers would save scarce water resources and minimize losses and wasteful use. Policies must also be identified and implemented so that groundwater and surface waters are not prone to the "tragedy of the commons." Undervaluing scarce water resources (surface waters and groundwater) can lead to their abuse (i.e., free electricity for pumping the groundwater for irrigation in Punjab, India). Land managers must be charged for the electricity and water used, and the cost must be eventually paid by the consumer. There is no such thing as free soil or free water. Channels of communications need to be established between researchers on the one hand and policy makers and land managers on the other. The lack of communication, due to weak institutions and inadequate extension/outreach, is a serious issue, which must be addressed.

TABLE 21.4
Site-Specific Researchable Priorities in Soil Water and Agronomic Productivity

Climate/Hydrology	Soil	Plant
Changes in temperature	Physical and hydrological properties	Choice of crops/plants, and rotational/spatial configuration
Alterations in hydrologic/energy balance	Potential and actual soil water storage capacities	Growing season duration, onset and end
Frequency of extreme events	Periods of soil water deficit	Nutrient–water interaction in relation to NPP
Probability of rainless periods (>10 days) during the growing season	Soil water regime in the subsoil	CO_2 fertilization effect
Predicting onset and cessation of rains during the growing season	Practices to reduce soil evaporation and runoff	Potential of the hydraulic lift
Runoff, infiltration, percolation relationships for extreme events	Techniques to enhance water productivity (aerobic rice, microirrigation, condensation irrigation)	Crop evaporative demand and consumptive use at different phenological stages

21.7 CONCLUSION

All terrestrial life depends directly or indirectly on soil water. The finite reserve, which comprises only 0.07% of renewable fresh water (17×10^3 km^3 out of a total of $24{,}589 \times 10^3$ km^3), may be prone to climate-induced alterations in the global hydrological cycle. The soil water reserve (green water) can be supplemented by the diversion of blue water (lakes and river) and recycling of adequately treated municipal (gray) water. Yet, soil water storage capacity and its efficient use depend on a wide range of site-specific factors related to climate, soil, land use, and cropping/farming systems. The potential effects of climate change on soil water storage and agronomic productivity also differ among ecoregions (temperate vs. tropical climate) and soil types. Therefore, it is important to identify site/soil-specific RMPs. Research data are needed with regard to the magnitude of projected climate change (temperature, precipitation, extreme events, growing season duration, and hydrologic balance), soil properties (physical and hydrologic properties, soil water storage capacity, periods of soil water deficit, and practices to enhance WP under rainfed and irrigated conditions), and plants (species, rotation sequences, seeding configuration, time of sowing, hydraulic lift, consumptive water use, nutrient–water interaction, and CO_2 fertilization effect). Policy interventions are needed to minimize excessive use of water, promote adoption of RMPs through payments for green water credit, and create a mechanism to charge a just price to the water user to avoid it being used as a common resource. Channels of communication must be developed between researchers, land managers, and policy makers for creating public awareness about the scarcity of this precious resource and the need for its sustainable use.

ABBREVIATIONS

AWC	Available water capacity
INM	Integrated nutrient management
IWM	Integrated water management
RFWR	Renewable freshwater resources
RMPs	Recommended management practices
WP	Water productivity
WUE	Water-use efficiency

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